TRANSACTIONS
OF THE
AMERICAN GEOPHYSICAL UNION

Volume 18

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Parts I and II

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NATIONAL RESEARCH COUNCIL

TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION

EIGHTEENTH ANNUAL MEETING

APRIL 28, 29, 30, 1937
WASHINGTON, D. C.

REGIONAL MEETING

JUNE 21 TO 26, 1937
DENVER, COLORADO

PART I

REPORTS AND PAPERS, WASHINGTON, D. C.
GENERAL ASSEMBLY AND SECTIONS OF GEODESY, SEISMOLOGY, METEOROLOGY, TERRESTRIAL MAGNETISM AND ELECTRICITY, OCEANOGRAPHY, AND VOLCANOLOGY

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
JULY, 1937

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PART II

REPORTS AND PAPERS

SECTION OF HYDROLOGY
WASHINGTON, D. C., APRIL 29 AND 30, 1937

SECTION OF HYDROLOGY
AND
SOUTH CONTINENTAL DIVIDE SNOW-SURVEY CONFERENCE
DENVER, COLORADO, JUNE 21 TO 26, 1937

[Part II includes (1) annual reports of permanent research committees for 1936-37 and papers before Section of Hydrology at Washington, and (2) papers before Section of Hydrology and before South Continental Divide Snow-Survey Conference at Denver]

INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now seven sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, and (g) Hydrology. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section; the Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology.

Annual assemblies of the Union and annual meetings of its sections for the discussion of reports and for symposia are held each year. The first 13 assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C. Besides the annual general assemblies and meetings of each of the seven sections held in Washington, D. C., meetings of the Section of Hydrology were held at Berkeley, California (1933 and 1934), at Pasadena, California (1936), and at Denver, Colorado (1937). The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 56; eighth, 1927, Bulletin No. 61; and ninth, 1929, Bulletin No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, fourteenth, fifteenth, sixteenth, and seventeenth annual meetings were published in June 1931, June 1932, June 1933, June 1934, August 1935, and July 1936, respectively, in the series of miscellaneous publications of the National Research Council. The present volume, also one of the miscellaneous publications of the Council, includes the transactions of the eighteenth annual meetings held at Washington, D. C., April 28, 29, and 30, 1937, and of the meeting of the Section of Hydrology at Denver, Colorado, June 21 to 26, 1937. At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The scientific session of the General Assembly was devoted to a symposium on theoretical and observational considerations of importance to further studies of the depths of the Earth. Five formal papers presented were: On the estimation of temperatures at moderate depths in the crust of the Earth; the external gravity-field and the interior of the Earth; deep-focus earthquakes and their implications; the Earth's interior as inferred from terrestrial magnetism; and the behavior of matter under extreme conditions. After an extended discussion the symposium was summarized by L. H. Adams.

Detailed reports were received from two special committees, namely, (1) on geophysical and geological study of oceanic basins and (2) on geophysical and geological study of continents.

Of the ten resolutions adopted, there were two on time-signals and accurate timekeeping, two on gravity-work, one on cooperating seismograph-station, one on amateur seismology, one on radio methods of upper-air research, and one on collection of basic data in hydrology. The other two were resolutions of thanks for privileges extended by the Smithsonian Institution and by the United States Geological Survey.

In the Section of Geodesy 13 papers and reports were presented. Five of these dealt with progress and development of geodetic operations and instruments in Canada, Central America, Mexico, and the United States; six related to gravimetric surveys, apparatus, interpretations, and relation of gravity-anomalies and geologic structure; one illustrated the utility of State plane-coordinate systems; and one reported on geodesy at the Edinburgh Assembly.

The Section of Seismology held one session. The 12 communications may be classified as follows: Theoretical interpretations and analysis, 4; individual earthquakes and seismic measurements, 2; research in engineering seismology and applications, 3; seismic instruments, 2; progress-report for the United States, 1.

The Section of Meteorology heard 12 papers which concerned theoretical meteorology (3), observations and technique (7), areal frequency of tornadoes (1), and meteorology at Edinburgh Assembly (1).

Fifteen communications were received by the Section of Terrestrial Magnetism and Electricity. These related to instruments and technique (3), ionosphere and magnetic correlations (4), cosmic radiation (2), solar relations (3), measures of magnetic activity (1), and terrestrial electricity (2). The Secretary submitted brief summaries of progress-reports dealing with magnetic and electric researches by eight organizations in Canada, Peru, Western Australia, and the United States, including Alaska, Hawaii, and Puerto Rico.

Twelve communications at the meeting of the Section of Oceanography concerned progress during the year of five governmental and private organizations doing oceanographic work in the United States and Canada. Five papers had to do with dynamical oceanography and ocean-currents. Two papers related to North Atlantic deep-sea cores and investigation of submarine topography.

Fifteen papers were submitted and discussed at two sessions of the Section of Volcanology. They dealt with igneous rocks, igneous activity, and volcanic formations.

There were four sessions of the Section of Hydrology--three for the presentation of reports and papers, and an evening smoker devoted to informal reports on the Edinburgh Assembly of the International Union of Geodesy and Geophysics and to discussion of plans for the Assembly of that Union scheduled for Washington in 1939. Twenty-seven papers, with discussions, may be roughly grouped as follows: Rainfall, infiltration, and ground-water, 10; stream-flow and flood-control, 8; geophysical methods and technique for determination of underground water, 6; and one each on wells, mine-water, snow-surveying, and chemical action. The Research Committee on Rainfall and Runoff, because of its extensive field, was divided into two in 1936, namely, on runoff and on rainfall; thus there are now ten permanent research committees in this Section. The annual reports of these committees were received and discussed at the three scientific sessions as follows: (1) Snow; (2) glaciers; (3) evaporation; (4) absorption and transpiration; (5) runoff; (6) physics of soil-moisture; (7) underground waters; (8) dynamics of streams; (9) chemistry of natural waters; (10) rainfall.

The regional meeting of the Section of Hydrology at Denver, Colorado, was arranged by a special committee of which R. J. Tipton was Chairman. Some 44 stimulating papers with discussions were presented during ten scheduled sessions, June 21 to 26, 1937. At the first session statements were presented by the President of the Union and by the Chairman and Vice-Chairman of the Section of Hydrology on the objectives of the Section and on the general scientific and national and international aspects and relations of its field. In the following sessions the papers related to consumptive use and return flow, rainfall and runoff, physics of soil-moisture, dynamics of streams, and underground waters. The two sessions of June 22 were held jointly with the Society of American Foresters, and the nine papers presented will be published in the official organ of that Society. The session on the afternoon of June 24 was devoted to attendance at the symposium of the Ecological Society of America on "The scientific aspects of the control of drifting soils." The session during the morning of June 25 and the two sessions of June 26 constituted the South Continental Divide Snow-Survey Conference, concluding with a movie film of snow-surveying and a round-table presentation of experiences and problems in snow-surveying.

The General Secretary edited the manuscripts for publication after some preliminary editing by the secretaries of sections. The volume of Transactions herewith includes, either in full or in abstract, 138 papers and reports presented during the eighteenth annual meeting at Washington and some 35 papers and reports (not elsewhere published) presented during the meetings at Denver of the Section of Hydrology and of the South Continental Divide Snow-Survey Conference. The cost of publication was met through allotment by the National Research Council for maintenance of the Union, annual dues of members of the Union, and contributions of money and of services from the Carnegie Institution of Washington, from the University of Nevada, from members of the Union, and especially from hydrologists both members and non-members. C. C. Ennis proof-read the typed copy, and the authors, except for a few who could not be reached, also revised their matter as prepared for publication. The final copy was prepared, as in past years, by J. J. Capello with the assistance of J. Birnman, and was planographed by the Columbia Planograph Company of Washington. Besides its obligation to authors, to members of committees, and to our colleagues in Canada, Central America, and Mexico, who contributed to the eighteenth annual meeting, the Union is indebted to W. C. Hendrix for preparing many drawings of which the originals submitted were not suited for planographic reproduction and to P. G. Ledig for photographic work.

The total membership of the Union April 30, 1937, was 928--a net gain of 160 during the past year. Thirty-three of the Union's members attended the seventh triennial assembly of the International Union of Geodesy and Geophysics in September, 1936, at Edinburgh, Scotland. The eighth triennial assembly of the International Union is to be held in 1939 at Washington, D. C.

These annual and regional meetings afford abundant evidence of the vital scientific and economic importance of geophysics. They further point out many new applications and problems of large immediate and potential value. As a pioneer in the dissemination of American progress in current geophysical research so vital to human activities, the continued publication of the Transactions of our Union is an important agency--one which serves to emphasize the urgent need of finding additional suitable means of prompt publication.

Jno. A. Fleming, General Secretary
American Geophysical Union

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AMERICAN GEOPHYSICAL UNION

Eighteenth Annual Meeting

GENERAL ASSEMBLY

Washington, D. C.
April 30, 1937

Reports and papers

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BUSINESS SESSION

REPORT OF THE GENERAL SECRETARY, MAY 1, 1936, TO APRIL 30, 1937

The minutes of the seventeenth annual meeting held May 1, 1936, were mimeographed and distributed to all members of the Union, to authors of papers presented at the meeting, and to officers of the International Union of Geodesy and Geophysics. No comments have been received suggesting any changes or corrections. A report of the seventeenth annual meeting, prepared by the General Secretary, was published in *Science* of July 17, 1936.

Since May 1, 1936, the Union has lost by death five members: E. E. Haslam, May 16, 1936, affiliated with the Section of Hydrology; C. F. Talman, July 24, 1936, affiliated with the Section of Meteorology; Henry M. Eakin, October 20, 1936, affiliated with the Section of Hydrology; Montrose W. Hayes, November 16, 1936, affiliated with the Section of Hydrology; D. L. Yarnell, March 9, 1937, affiliated with the sections of Meteorology and Hydrology. The General Secretary, on behalf of the Union, has expressed deep sympathy to each of the bereaved families.

The total membership of the Union April 30, 1937, is 928, a gain of 160 during the past year. An alphabetical address-list of members showing also their Section affiliations was prepared and distributed to all members as of date January 20, 1937. Because of the augmented membership and the greatly increased volume of work incident particularly to the annual meeting and the publication of the *Transactions*, the Executive Committee has approved the employment of a full-time clerical assistant for the General Secretary's office from July 1, 1937, and has adopted dues of $3.00 per year beginning with the calendar year 1938 to meet this expenditure and to insure the adequate maintenance of the publication of the *Transactions* which have proved so valuable in bringing together in one place the yearly record of American progress in the Earth sciences.

The Executive Committee held two meetings since the last report (July 31, 1936, and January 29, 1937). Copies of the minutes of these meetings were distributed to members of the Executive Committee and to officers of the sections. The necessary arrangements were made for the eighteenth annual meetings of the Union and of its sections in Washington April 28, 29, and 30, 1937. The program for the scientific sessions includes over 110 papers and progress-reports.

The General Secretary edited and prepared for publication the manuscripts of 161 individual papers and reports presented at the seventeenth annual meetings of the Union and of its sections held April 30 and May 1 and 2, 1936, at Washington, and at the Pacific Coast meeting of the Section of Hydrology held January 31 and February 1, 1936, at Pasadena, which included the Western Interstate Snow-Survey Conference. Eighteen hundred bound copies of Part I (pages 1 to 260) and Part II (pages 261 to 564) were planographed. Over 1600 complete copies of the *Transactions* for 1936 have been distributed to members of the Union, to authors of papers presented, to foreign geophysicists including members and non-members of national committees for geodesy and geophysics, to institutions and scientific societies, to review periodicals, to persons on the regular mailing-list of the National Research Council, and by sale. An unusually large number of reprints were purchased by authors.

The publication of the *Transactions* for 1936 was made possible through allotment of $400 by the National Research Council for maintenance of the Union, annual dues from members of the Union, contributions solicited by the Section of Hydrology, contribution from the Carnegie Institution of Washington and proceeds from sales resulting chiefly from activities of the Section of Hydrology.

The National Research Council has included in its estimates for the fiscal year ending June 30, 1938, $400 for Union expenditures. A budget totaling $4058 has been approved by the Executive Committee of the Union for expenses of publication and maintenance during that fiscal year. The estimated income includes: (1) Balance in bank July 1, 1937, $1000; (2) income from 1937 dues, $1658; (3) grant from National Research Council for which application has been made, $400; (4) sales of *Transactions* and reprints, $1000. The Executive Committee has authorized the publication of the *Transactions* for 1937, the number of pages to be determined by receipts and usual expenses of maintenance.

An Auditing Committee examined the accounts of the Union as of date December 31, 1936, and found the receipts and disbursements exactly as stated in the General Secretary's report of that date.

The Union continued its cooperation with the Division of Physical Sciences of the National Research Council in the preparation of special bulletins on geophysical methods, instruments, results, etc. The manuscripts for eight of the ten chapters for the manual on terrestrial magnetism and electricity, together with illustrations, have been completed. The committee charged with the preparation of the manual on hydrology is now well organized and is receiving manuscripts on selected topics by various members.

A letter has been received from the Secretary of the Geological Society of America reporting that the Society has decided to decline the request of the Union for a grant to aid in the establishment of an American Journal of Geophysics.

In view of the additional details requested by Naval Communications in connection with consideration of the resolution passed at the seventeenth annual meeting on time-signal service and the need of additional information regarding the use and demands for such service from various sources throughout the country, a Special Committee on Time-Signal Service has been appointed and charged with the responsibility of maintaining continued contact with various organizations in the United States interested in such service.

The Special Committee on Geophysical and Geological Study of Oceanic Basins reported that the cooperative expedition sponsored by the Committee with the cooperation of the United States Navy, the United States Coast and Geodetic Survey, the Bell Telephone Laboratories, and the American Philosophical Society was successfully concluded January 15, 1937, when the submarine Barracuda returned to Philadelphia. The preliminary results of the expedition indicate that a strip of negative gravity-anomalies parallels the island-arc from the east end of Cuba throughout its length. A notable discovery in the Anegada Passage was an uncharted bank of considerable area at 20 fathoms where the present charts showed 1000 fathoms. This was the first under-sea gravimetric expedition with entirely American personnel. A marked improvement in the technique of gravimetric work resulted from the use of a crystal clock to control time-intervals which was made possible by the generous collaboration of the Bell Telephone Laboratories.

The Special Committee on Geophysical and Geological Study of Continents made considerable progress during the past year in working up maps to depict basement-structure of the continents and its regional correlations with gravitational, seismic, magnetic and electric, and thermal geophysical results.

The American Geophysical Union maintained its relations with the international body. The Sixth General Assembly of the International Union of Geodesy and Geophysics was held at Edinburgh, Scotland, September 15 to 26, 1936. Our Union was represented by the following as delegates: Harry Bateman, Lloyd V. Berkner, William Bowie, James E. Church, Edwin G. Conklin, Arthur L. Day, Carl Elges, Richard M. Field, John A. Fleming, Lawrence M. Gould, Beno Gutenberg, Harry D. Harradon, Nicholas H. Heck, Paul R. Heyl, William H. Hobbs, Columbus Iselin, Walter D. Lambert, Joseph Lynch, James B. Macelwane, Walter W. McLaughlin, Oscar E. Meinzer, William J. Peters, Roger Revelle, Harlan T. Stetson, Thomas G. Thompson, Clinton L. Utterback, T. Wayland Vaughan, R. Hanson Weightman, and Oliver R. Wulf. Chaim L. Pekeris and Carl G. Rossby, members of the Union, attended as guests since they are not citizens of the United States; Elliott B. Strauss, Assistant Naval Attaché of the American Embassy at London, and H. O. Wentworth also attended as guests, as well as 18 ladies. The total attendance from the United States was 51 delegates and guests. The Assembly was successful in every way, over 400 delegates and guests taking part. The invitation received from the National Research Council of the United States in accordance with the action taken by our Executive Committee on behalf of the American Geophysical Union to hold the Seventh General Assembly of the International Union of Geodesy and Geophysics and of its associations at Washington, D. C., in 1939, probably during September, was accepted.

At the Edinburgh Assembly, R. M. Field was appointed Chairman and J. A. Fleming was appointed Secretary of a newly-formed Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics. A communication regarding this Commission, its history, meetings, and purposes, prepared by the Chairman and Secretary, was published in Science of February 12, 1937.

The General Secretary of the International Union of Geodesy and Geophysics reported that he has now received payment of dues from the United States as an adhering country for 1935 and 1936.

The increase in membership during the past year and the wide geographic distribution of new members again evidence continuing and increasing interest in geophysics resulting, in large part, through the preparation and widespread distribution of the annual volume of Transactions of the Union which cross-section American progress in Earth sciences.

Jno. A. Fleming, General Secretary

REPORTS OF SPECIAL COMMITTEES

Time-Signal Service (H. E. McComb, Chairman)--The Committee reported that a large number of users of United States Navy Department time-signals in the fields of applied geophysics, geodesy, and seismology have supplied information relative to the extent of the use of these signals. The general character and number of these communications prove that the time-signals are used in a wide variety of scientific investigations. The Committee will supply detailed information on specific signals in its final report to the Union. Several users have reported serious difficulties in the reception of the 9425-kilocycle signal due to interference from foreign stations. Others have suggested the desirability of having additional signals on some of the standard frequencies now on the schedule.

Geophysical and Geological Study of Continents (W. T. Thom, Jr., Chairman)--The extended report of this Committee is printed in full on pages 17-20.

Geophysical and Geological Study of Oceanic Basins (R. M. Field, Chairman)--The extended report of this Committee is printed in full on pages 13-17.

Cooperation with International Commission for the Study of Tidal Waves (F. Neumann, Chairman)--Reports of tidal waves received have been forwarded periodically to the Chairman of the International Commission.

American Journal of Geophysics (J. A. Fleming, Chairman)--As no grants-in-aid from outside sources were made, it has not been possible to inaugurate the proposed American Journal of Geophysics this year. For the present, the Committee feels it desirable to continue the *Transactions* as heretofore, meanwhile continuing efforts to obtain support to realize eventually the proposal as favorably acted upon at the seventeenth annual meeting in 1936.

Arrangements for the 1939 Assembly of the International Union of Geodesy and Geophysics (N. H. Heck, Chairman)--Following meetings of the Committee, the Chairman and General Secretary canvassed the situation carefully through numerous conferences with groups and individuals. The recommendations of the Committee were as follows:

> "It is recommended that the executive officer assigned with the responsibility of carrying on the arrangements for the Assembly should continue to be in charge through the Assembly with the advice of, and reporting progress from time to time to, the Executive Committee of the Union. The chairmen of the several committees concerned, as also any persons designated as local secretaries for the International associations, should also continue to serve from the time of appointment through the Assembly.
>
> "It is further recommended that the following committees be arranged for: (1) Organization committee; (2) Finance committee, with subcommittees relating to participation of (a) government and (b) other organizations; (3) Committee on meeting places, hotels, and dormitories; (4) Committee on entertainment, with subcommittees relating to (a) International Union as a whole, (b) ladies' entertainment, and (c) individual Association entertainment; (5) Committee on communications (one of the duties of this committee will be that a proper number of stenographers, interpreters, and clerks are supplied, as well as ample provision made for reproduction by mimeographing or planographing of the minutes, reports, and other office matters dealing with the Assembly); (6) Committee on travel arrangements including also special field-trips after the meeting and especially any concerned with geophysical demonstrations (this committee's duties shall include also arrangements for miscellaneous travel after the Assembly); (7) Committee on coordinated interests (this committee will solicit cooperation of the many societies and organizations interested in geophysics and especially the several South American governments); (8) Committee on exhibits; (9) Committee of local secretaries of Section (the duty of the local secretary is to correspond with the secretaries and officers of the International associations with regard to details for their respective meetings during the Assembly); (10) Committee on publicity."

RESOLUTIONS ADOPTED

The Committee on Resolutions of the Union (H. S. Rappleye, Chairman; H. N. Eaton, and H. F. Johnston) submitted the following ten resolutions, each of which was unanimously adopted:

(I) RESOLUTION ON THE COOPERATION OF THE SMITHSONIAN INSTITUTION IN FURNISHING MEETING FACILITIES FOR THE AMERICAN GEOPHYSICAL UNION

WHEREAS, The meetings of the National Academy of Sciences utilized all available space in the National Academy and Research Council Building on Wednesday, April 28, 1937, and

WHEREAS, The sections of Oceanography, Volcanology, and Terrestrial Magnetism and Electricity of the American Geophysical Union were in need of meeting places on that date, and

WHEREAS, The administrative staff of the Smithsonian Institution offered space and projection facilities in the National Museum Building for the meetings of these three sections on April 28, 1937, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of this generous cooperation in facilitating the holding of the meetings of these three sections, and be it further

RESOLVED, That a copy of this resolution be sent to the Secretary of the Smithsonian Institution.

(II) RESOLUTION ON UNITED STATES NAVY TIME-SIGNALS

WHEREAS, The radio time-signal service maintained by the United States Navy Department through the Naval Observatory and the Office of Naval Communications is essential for the economical and efficient continuation of many scientific projects of a geophysical nature, and

WHEREAS, This service has been very effectively maintained and improved during the past year to the great benefit of seismological studies and geodetic operations and other scientific investigations, therefore be it

RESOLVED, That the American Geophysical Union in joint assembly express its deep appreciation and gratitude for this valuable scientific cooperation, and be it further

RESOLVED, That a copy of this resolution be sent to the Secretary of the Navy, to the Chief of the Office of Naval Communications, and to the Superintendent of the United States Naval Observatory.

(III) RESOLUTION ON CONTRIBUTION TO ACCURATE TIMEKEEPING BY BELL TELEPHONE LABORATORIES OF NEW YORK

WHEREAS, The results obtained on the recent Gravity-at-Sea Expedition to the West Indies were greatly increased in precision by the use of an improved crystal-chronometer developed by the Bell Telephone Laboratories of New York and loaned by that Organization to the Expedition, and

WHEREAS, This new timepiece gives promise of having great value in many kinds of scientific work involving accurate time, therefore be it

RESOLVED, That the American Geophysical Union express its high appreciation of the contribution of the Bell Telephone Laboratories of New York to the success of the West Indies Expedition, and be it further

RESOLVED, That the American Geophysical Union express the hope that the Bell Telephone Laboratories of New York will continue its splendid cooperation in scientific investigations by making chronometers of this type available for other investigators needing precise timing-devices, and be it further

RESOLVED, That a copy of this resolution be sent to the President of the Bell Telephone Laboratories of New York.

(IV) RESOLUTION ON GRAVITY-WORK AT SEA BY THE UNITED STATES NAVY

WHEREAS, The third expedition to the West Indies for the determination of gravity at sea was successfully carried out during December, 1936, and January, 1937, by the cooperation of the United States Navy, the American Geophysical Union, and other organizations, and

WHEREAS, The results of this expedition are of great scientific value and were made possible by the use of a submarine with its specially trained operating personnel, and by the use of the accurate radio time-signals and many other services which were made available by the United States Navy, therefore be it

RESOLVED, That the American Geophysical Union express its high appreciation to the United States Navy Department for its invaluable contribution to this important geophysical investigation of oceanic areas, and be it further

RESOLVED, That the American Geophysical Union express the hope that the United States Navy will continue to promote this important work by making available, whenever practicable, a submarine for other expeditions to determine gravity at sea, provided qualified observers and suitable apparatus are furnished by the cooperation of interested agencies, and be it further

RESOLVED, That copies of this resolution be sent to the President of the United States and to the Secretary of the Navy.

(V) RESOLUTION ON COOPERATION OF AMERICAN PHILOSOPHICAL SOCIETY

WHEREAS, The American Philosophical Society cooperated in the recent Gravity-at-Sea Expedition to the West Indies by making a grant to cover certain expenses of the Expedition not otherwise provided for, and

WHEREAS, This grant contributed materially to the success of the Expedition by making available certain instruments and part of the scientific personnel, therefore be it

RESOLVED, That the American Geophysical Union express its high appreciation of the contribution of the American Philosophical Society to the success of the Expedition, and be it further

RESOLVED, That a copy of this resolution be sent to the President of the American Philosophical Society.

(VI) RESOLUTION ON THE SEISMOGRAPH STATION AT PENNSYLVANIA STATE COLLEGE

WHEREAS, The preliminary seismological work at Pennsylvania State College by the Department of Geophysics has resulted in valuable contributions to the study of local and teleseismic disturbances, and

WHEREAS, The Station has been greatly handicapped both as to adequate instrumental equipment and a suitable seismograph-vault, therefore be it

RESOLVED, That it is the hope of the American Geophysical Union that it will be possible to provide the Pennsylvania State College with a modern and well-equipped seismological observatory for the continuation and extension of its seismological investigations and cooperative work, and be it further

RESOLVED, That copies of this resolution be sent to the President of Pennsylvania State College and to the Dean of the School of Mineral Industries of Pennsylvania State College.

(VII) RESOLUTION ON AMATEUR SEISMOLOGY

WHEREAS, There has been a great demand from amateurs for information regarding the design and operation of seismic equipment, and

WHEREAS, The cooperation of amateur seismologists would eventually yield valuable data and also lead to a greater appreciation of the value of seismology on the part of the public, and

WHEREAS, A Committee on Amateur Seismology has been formed by the Eastern Section of the Seismological Society of America, therefore be it

RESOLVED, That the American Geophysical Union wishes to encourage this movement and endorses the action of the Eastern Section of the Seismological Society of America, and be it further

RESOLVED, That copies of this resolution be sent to the Chairman of the Eastern Section of the Seismological Society of America and to the Chairman of its Committee on Amateur Seismology.

(VIII) RESOLUTION ON UPPER-AIR REPORT BY RADIO-METEOROGRAPH

WHEREAS, There is urgent need (1) for upper-air reports by radio-meteorograph to great heights in all weather at numerous stations for purposes of aviation, forecasting, and meteorological research, (2) for active research into the meteorological significance of the new data, and (3) for the building up of an adequate body of university-trained meteorologists in the United States, and

WHEREAS, These needs can be met most effectively by research institutions and universities in cooperation with Government weather-services, therefore be it

RESOLVED, That the American Geophysical Union heartily commend, as an effective means of furthering American meteorology and safe flying, the five-year cooperative program of research and instruction in aerology and aeronautical meteorology proposed by the Blue Hill Meteorological Observatory of Harvard University, and that it urge financial support for this program by airlines, individuals, and research foundations, and be it further

RESOLVED, That copies of this resolution be sent to the Director of the Blue Hill Meteorological Observatory and to the Chief of the United States Weather Bureau.

(IX) RESOLUTION ON THE COLLECTION OF BASIC DATA IN HYDROLOGY

WHEREAS, In all activities of the Section of Hydrology, so much dependence is placed upon the heritage of basic data collected in past years, and

WHEREAS, The continuance of progress toward the solution of many problems still unanswered is so dependent upon the establishment of a sound basis of observational data by our generation to be used by those that follow, and

WHEREAS, At present so little is known of the part played by the ability of the soil to absorb or retain moisture, in proportion to its importance in so many hydrologic studies, particularly the influence of such elements as frost, snow-cover, growing crops, etc., therefore be it

RESOLVED, That formal recognition be taken of the foresight of all agencies, both Federal and non-Federal, who have preserved for Science this invaluable record, and of the personal interest and sacrifice to duty on the part of the men who have given devoted service, and be it further

RESOLVED, That encouragement be given to the collection of basic hydrologic data, and in particular to the recommendations of the Water Resources Committee in outlining a program of work that is greatly needed, and be it further

RESOLVED, That all agencies engaged in the collection of necessary data be urged to give particular attention to these factors, noting specifically the dates between which the ground becomes frozen, or in any way non-receptive to precipitation.

(X) RESOLUTION ON COOPERATION OF UNITED STATES GEOLOGICAL SURVEY IN FURNISHING A MEETING PLACE FOR AMERICAN GEOPHYSICAL UNION

WHEREAS, Room 5243 (Director's Conference Room) of the United States Geological Survey was made available for the use of the American Geophysical Union on the evening of April 29, 1937, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of this courtesy extended by the United States Geological Survey, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Interior and to the Director of the United States Geological Survey.

REPORTS

REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF OCEANIC BASINS

R. M. Field, Chairman

D. C. Barton
W. Bowie
W. H. Bucher
M. Ewing
J. A. Fleming
C. A. Heiland
H. H. Hess
C. O. Iselin
Arthur Keith
J. B. Macelwane
H. A. Marmer
F. E. Matthes
R. S. Patton
F. P. Shepard
H. C. Stetson
H. U. Sverdrup
P. D. Trask
W. H. Twenhofel
P. Weaver
F. E. Wright

During the past year the principal collective activity of your Committee has been concentrated on completing the plans and the execution of the gravimetric and submarine topographic expedition to the West Indies. Your Chairman, together with Dr. Maurice Ewing and Dr. H. H. Hess, served as a subcommittee with Captain L.R.Leahy, Hydrographer of the United States Navy. Dr. Ewing was appointed chief scientist of the expedition, and was assisted by Lt. A. J. Hoskinson of the United States Coast and Geodetic Survey and Dr. Hess.

Relatively late in the plans, it was decided to attempt to change the method of timing the pendulums. This would have proved a somewhat dangerous decision had it not been for the fundamental cooperation of the Bell Telephone Laboratories of New York, which, through its President, Dr. F. B. Jewett, and Mr. W. A. Marrison, provided a crystal chronometer, which was adapted to the Vening Meinesz apparatus. The Committee is deeply indebted to Mr. Marrison for this great improvement in the determination of gravity on land, as well as at sea.

The preliminary report on the Navy-Geophysical Union Gravity Expedition is printed elsewhere in the Transactions, and is also referred to in the Secretary's report, but your Chairman wishes particularly to express the thanks of the Committee on Geophysical and Geological Study of Oceanic Basins to Lt. Hoskinson, and to two of its members, Dr. Ewing and Dr. Hess, for their labors in connection with the first all-American marine gravity-expedition. It should be added that only those who are fully acquainted with the large amount of delicate and original technique connected with such an expedition can fully appreciate the responsibilities which were assumed and so successfully discharged by our colleagues. Elsewhere in the Transactions are cited the appreciation and thanks of the American Geophysical Union, as expressed in resolutions, to the American Philosophical Society, the United States Navy, the United States Coast and Geodetic Survey, and the Bell Telephone Laboratories.

Upon the return of the expedition to Philadelphia, January 15, 1937, particular attention was paid to the continuance of the submarine seismic experiment beyond the continental margin and into the greater depths of the oceanic basins. After considerable consultation, both here and abroad, it was the consensus of opinion, especially as expressed at the Assembly of the International Union of Geodesy and Geophysics at Edinburgh last fall, that the further development of the submarine seismic technique was of the utmost importance.

The Woods Hole Oceanographic Institution continued its interest in the matter, and its Director, Dr. Henry B. Bigelow, offered your Committee the further use of the Atlantis, provided that a feasible plan of operations could be guaranteed and financed. Much care and thought were given to this matter as soon as it was definitely understood that a vessel and trained crew might be available. After consultation with a number of experts, your Chairman asked Captain N. H. Heck and Columbus Iselin of your Committee if they would serve as a special planning and operating subcommittee, with Dr. Ewing as Chairman. Application was made to the Geological Society of America, through Dr. Ewing, for the absolute minimum of funds necessary to carry out the project, it being fully appreciated that, as in the case of the last gravity-expedition, the major necessary contributions had already been assured through other cooperative agencies. It is not expected that the many problems associated with the adaptation of the seismic method to oceanic depths will be solved this fall, or is it taken for granted that even the preliminary experiments will be entirely successful. We do, however, feel reasonably assured that the problem can and will be solved, and that a new and exceedingly important geophysical technique will ultimately be added to the only one now available (gravity) for the exploration of the structure of oceanic basins. Other deliberations and activities of your Committee during the past year are discussed under the following headings:

Gravity--Continued cooperation with the Special Committee on Geophysical and Geological Study of Continents, especially in relation to: (1) Geophysical-geological study of island-arcs and the problem of geosynclines; (2) geological significance of gravity-anomalies, in general; (3) Pre-Cretaceous structure of the Atlantic continental margin of the United States.

At the request of Professor Miller and Dr. Ewing, the Coast and Geodetic Survey ran a traverse of 16 gravimetric determinations parallel to the seismic profile of the coastal plain and submerged continental shelf previously determined. "Sixteen gravity-determinations were made along nearly a straight line from a point southwest of Richmond to one on the Atlantic Coast a few miles southeast of Norfolk. The two most noticeable characteristics about the isostatic profile are, first, its 'down-warped' slope toward the coast-line, and, second, the very pronounced break," some 30 miles from tide-water [C. H. Swick, Bull. Amer. Assoc. Petrol. Geol., v. 21, pp. 333-339, 1937]. It is particularly interesting to note that this gravity-profile is parallel to but somewhat steeper than the seismic profile, and that the latter unquestionably represents the peneplained surface of the crystallines as it passes beneath the Cretaceous overlap. Upon its return to Philadelphia from the West Indies Gravity-Expedition, the submarine Barracuda determined two gravity-stations off the seaward end of this profile, and Dr. Vening Meinesz in a Dutch submarine determined four more. The anomalies for these stations have not yet been computed, but it is expected that they will be available before the extension of the oceanic seismic profile this fall. The adaptation of the crystal chronometer to the Vening Meinesz apparatus so increased the efficiency and accuracy of this machine that arrangements were made with the United States Coast and Geodetic Survey to check the Vening Meinesz apparatus and crystal clock against pendulum-stations on land. This is now being done in the vicinity of Bethlehem, Pennsylvania.

Dr. Ewing has called to the attention of your Committee that, in the case of the vertical gradient of gravity, "the theoretical value exceeds the mean of the four experimental determinations (made 1890-1900) in the ratio 315/304, or five per cent. Common practice in gravimeter-surveys is to use assumed values of gradient to calibrate the instruments. Data accumulated by these private surveys will eventually be contributed to the United States Coast and Geodetic Survey for use in the gravimetric map of the United States. It is urgent that the calibration of the instruments be accurate if the results are to be of highest scientific value. The formula now used to correct the Vening Meinesz measurements of gravity at sea for depth of submergence of the submarine depends upon this gradient." It is, therefore, suggested that the vertical gradient of gravity be checked by "simply carrying the instruments to various heights in tall buildings. The change of gravity with elevation above the surface is about one milligal for each ten feet. The Empire State Building is 1248 feet high. The difference in gravity between top and bottom should be about 125 milligals. The Vening Meinesz instrument, with the crystal chronometer, will give results reliable to one milligal. By measuring at four or more levels, it would be possible to determine the gradient to within one per cent. Since the vertical gradient is influenced by irregular mass-distribution near the measuring instrument, it would also be necessary to make similar measurements in a number of localities".... but, "there are at least 20 cities in the eastern half of the United States having buildings 450 feet or more in height. In all of these a gravimeter would give precise and useful results. The change of gravity with depth of submergence in the sea is (according to the Vening Meinesz formula) about 0.07 milligal per foot; for a submergence of 2000 feet the change in gravity would be 140 milligals; for 3000 feet, 210 milligals. A Vening Meinesz type apparatus placed in a bathysphere would determine this difference with an accuracy approaching one per cent."

The following projects are, therefore, being considered:

(a) To use the Vening Meinesz apparatus to measure vertical gradient of gravity in the Empire State Building with an accuracy of ± 1 per cent.
(b) To use a properly calibrated gravimeter to measure the vertical gradient of gravity in tall buildings in several different cities, with an accuracy of ± 1/10 per cent.
(c) To use a Vening Meinesz apparatus in a bathysphere to measure the vertical gradient of gravity at selected sea-stations with an accuracy of ± 1 per cent.

It is expected that (a) could be done early this summer and that (b) could also be partly, if not entirely, completed within a relatively short time. Certain mechanical and marine problems and difficulties are presented by (c) which will require more time for their solution. However, if, after a still further consideration of the history of the problem, both experimental and mathematical, the experiment is deemed worth while, there is good reason to believe that it will be possible of accomplishment.

Early this spring Sir Hubert Wilkins consulted your Committee relative to the Vening Meinesz apparatus, now in this country, and in which he has a priority right. As the determination of gravity in the North Polar Ocean is one of the objectives of Sir Hubert's submarine expedition, he has also referred the plans of this part of the program to your Committee, as well as to the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics. Naturally, we are deeply interested in the "gravity-field" of the Arctic oceanic basin, for, as expressed by Gutenberg, "Some data concerning the North Polar Basin indicate that the structure there is similar to that in the Pacific Ocean; the sial is either missing or very thin."

After conference with Dr. Bigelow and Dr. Sverdrup, it has been suggested to Professor O. T. Jones, Dr. Harold Jeffreys, and Dr. E. C. Bullard that the Vening Meinesz apparatus be sent to the University of Cambridge until such time as it may be installed in the specially designed submarine now being built in Great Britain. It is hoped that our English colleagues will accept the temporary custodianship of the Vening Meinesz apparatus and also that they will continue to interest the British Admiralty in the determination of gravity at sea.

Seismology--Elsewhere in the Transactions, the Chairman of your Committee has expressed his views on the importance of the application of seismological techniques to the structural study of oceanic basins. Plans for the continuation of the application of the "artificial" seismic method to the study of the suboceanic lithosphere have already been described in this report. It remains, however, to call attention again to the important studies of Gutenberg and Richter (Bull. Geol. Soc. Amer., v. 47, pp. 1587-1610, 1936) on the relative rates of travel of shallow earthquake-waves through (1) the continents and (2) the Pacific, Atlantic, and Indian oceans. Captain N. H. Heck has suggested that the conclusions of Gutenberg and Richter as to the presence of an appreciable thickness of sial under the Atlantic Ocean be further tested by an analysis of the shallow earthquake-waves whose epicenters occur in the narrow part of the Atlantic between South America and Africa. Records of earthquakes from this region which reach the North American stations will have travelled entirely through the Atlantic suboceanic lithosphere, while records of earthquakes which have been recorded at stations in northwestern Europe will have travelled, most of the distance, through rocks of the continental type. Dr. H. Landsberg has become interested in this problem, especially from the point of view of the re-analysis of the data as suggested.

Terrestrial magnetism--In an excellent review of the history of oceanic magnetic surveys, J. A. Fleming states in a report prepared for the National Academy, "Attention may be called to the apparent diminution of the intensity of the Earth's magnetic field discovered by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. As determined by the data thus far obtained, this diminution is marked over oceanic areas, especially in the Southern Hemisphere .... From observed earthquake-wave velocities and reflections for different regions and depths the crustal layer, which under most of the continental and water-covered continental structures is about 25 km thick, is indicated as either lacking or quite thin under the Pacific Ocean including possibly the Arctic region. Under the Pacific Ocean the basic surface of the Earth's mantle is (supposed by some authorities to be) practically exposed. There then we may expect different geological and geographical properties from those found elsewhere. Thus the observed longitudinal and latitudinal distribution of magnetic secular-variation agrees with that of the land-areas, as witness the moderate rates of annual change over the Pacific as compared with those over the Atlantic and adjoining continental areas. Further data bearing on correlation thus indicated between the surface-distribution of the secular-change activity promise conclusions concerning secular-variation processes localized in the crustal layer (sial) and only where this layer is present. Thus continued secular-variation surveys at sea should bring together seismic and magnetic methods of approach to crustal adjustments and possibly gravimetric work."

Submarine and suboceanic topography--In order to make use of all available sonic sounding data for the forthcoming geophysical-structural-topographic map of the West Indies, the request by Dr. Hess for recent soundings made by the British Admiralty in the Caribbean has been transmitted to Admiral Edgell, Hydrographer, through the Commission on Continental and Oceanic Structure. Also, at the request of your Committee, the Acting Hydrographer, Captain Kays, United States Navy, has approved the desirability for further soundings in the Caribbean. A chart of proposed soundings has been prepared and approved by the Hydrographic Office and Bureau of Operations of the United States Navy, and the project will be carried out as Naval ships become available to operate in the Caribbean Area. It is expected, therefore, that additional and exceedingly valuable data will be available by the time of the final publication by the Hydrographic Office of the 1936-37 United States Navy-American Geophysical Union Gravimetric Expedition.

The past year has seen an increasing interest in the problem of submarine canyons, primarily because of the remarkably accurate data (both as to depth and fix) which the United States Coast and Geodetic Survey is obtaining off both the Atlantic and Pacific coasts. Because as soon as adequate soundings are available their topographic interpretation is relatively simple, and also because the resulting topographic maps strongly suggest great canyons, it is but natural that these phenomena should have easily compelled the attention of a number of geologists. This matter has been recently discussed more fully elsewhere (R. M. Field, J. Wash. Acad. Sci., v. 27, pp. 181-195, 1937); but it should be added that the balance of opinion of your Committee, as well as that of the International Commission, is that more attention should be paid to the adequate and accurate mapping of certain selected oceanic areas, such as the Middle Atlantic Ridge, the Gulf-Caribbean Region, the West Coast of South America, and the North Atlantic. Further, it should be noted that soundings are needed for the intercanyon areas off the Atlantic Coast, and also off the mouths of the canyons on the oceanic floor. In regard to the several hypotheses which have been proposed to account for the origin of the canyons, it would appear as if undue emphasis were placed on purely continental and climatic controls without the proper consideration of possible diastrophic control within the oceanic basins themselves. Not one of the "canyon-hypotheses" is reasonably "acceptable" at the present time, and it is highly probably that the present lack of data on the oceanic areas is the principal underlying, if partly subconscious, reason for the present "canyon-hypotheses."

Those who have given considerable thought to the topographic surveying of oceanic basins agree that, while the geophysical technique is now available, the plan for carrying out such a survey is much more difficult than the continuation of the submarine topographic surveying of the continental shelves. Those existing American agencies which are best fitted to extend submarine mapping over the oceanic areas are, at present, prohibited from doing so by governmental regulations; and, at present, there is no international agreement by which this may be accomplished except through the interchange of sounding data as acquired by the hydrographic offices of certain navies, and as acquired through relatively rare and independent oceanographic surveys. Sonic data which are now being acquired by these means are, however, not of sufficient accuracy, particularly in relation to fix. What is particularly needed is an international agreement by which the more accurate methods of submarine mapping may be gradually and continuously applied to significant oceanic areas, and that the interested maritime nations will help and encourage their agencies, both civil and naval, in starting and continuing this work. This is perhaps the first and most fundamental problem to be considered by the new Commission of the International Union of Geodesy and Geophysics.

Vessels--During the past year, there has been considerable discussion relative to the acquisition and operation of a special vessel which could devote its whole time to the geophysical-geological study of the suboceanic lithosphere. The majority opinion regarding this problem appears to be as follows:

(1) Because of the relatively rapid advances which are expected in the several lines of marine geophysical techniques during the next few years, it would seem inadvisable to attempt to "design" and equip such a vessel at the present time. This opinion does not, however, include the building of vessels for magnetic studies, especially as such vessels, because of their construction and duties, may not be expected, in general, to do types of geophysical exploration other than sounding.

(2) The maintenance and operation of the proposed geophysical survey-vessel would be altogether too costly, especially if other numerous agencies are already available for the same purposes. Further, any funds now available for such a vessel could be much more profitably expended on research relating to the adaptation of present, and the invention of new, marine geophysical apparatus and methods.

(3) The cooperation which your Committee has received, both individually and collectively, from the leading oceanographic laboratories of the United States, both on the Atlantic and Pacific coasts, has been most encouraging. It must also be recognized that few geologists or geophysicists are "at home" at sea, especially in relatively small boats, and even a smaller percentage have any knowledge of vessels or navigation. Finally, a still smaller number (almost to the vanishing point) are acquainted with the main problems pertaining to the handling of miles of cables in the open ocean, which knowledge is chiefly confined to such agencies as the United

States Coast and Geodetic Survey and the Western Union Telegraph Company. It would, therefore, seem, for the present at least, that all funds which are, or may be, available should be expended in cooperation with existing agencies.

(4) It is highly probable that submarines will continue to play an active part in the geophysical-structural survey of oceanic basins. Sir Hubert Wilkins is having a submarine designed for geophysical exploration. It is possible that, in the near future, one or more submarines operated by civilian crews may become a necessary and even standard equipment for marine geophysical research. In any event, it is by no means certain that surface-vessels alone will provide the necessary transport for the marine geophysicist; and, at the present time, the geophysical-structural exploration of the suboceanic lithosphere would be practically at a standstill were it not for the splendid cooperation of the Dutch and American navies.

Conclusions

(1) Since its inception the policy of your Committee has been to devote its collective energies to the promotion and development of marine geophysical techniques, and especially those which required the cooperation of large and sometimes diverse cooperative agencies. This policy has been carried out in two ways: (a) By widespread consultation, both within and without the membership of the American Geophysical Union; (b) by the planning and execution of experiments and expeditions. Certain members of your Committee have undertaken certain serious and laborious responsibilities, in order to try out and prove what might be termed test cases in primary, marine-geophysical research. It should not be necessarily assumed, however, that your Committee will continue to operate different types of marine-geophysical surveys beyond the point where such surveys have been proved to be practical and effective.

(2) The development of marine-geophysical surveying has already reached a stage where its further progress depends primarily on the following factors:

(a) Increase of technical personnel--This can be accomplished only through the addition of one or two new younger men to each type of expedition. Necessarily, at the beginning, this will require some personal sacrifice of the time and ambition of the few men who have been responsible for the progress of the work in this country since 1932.

(b) Continued and ever-increasing cooperation of those large and highly important cooperative agencies, especially large industrial research laboratories and federal bureaus and departments, both naval and civilian.

(c) Increasing international cooperation, especially such as may be approved and supported by those countries adhering to the International Union of Geodesy and Geophysics.

(d) The publication, at an early date, of an international report on the present status of marine-geophysical-surveying, with special emphasis on methods and techniques, and an impartial and historical review of existing geological and geophysical hypotheses as they may be related to the further geophysical exploration of the suboceanic lithosphere.

(e) It is particularly significant that the American marine biological laboratories have shown an increasing interest in submarine geology, as well as in physical oceanography. Thus geophysics is beginning to play an ever-increasing part in oceanographic research, and it is highly essential that the American Geophysical Union should do all that it can to encourage and support the work of our oceanographic research institutions, and especially those which are maintaining ocean-going vessels with well-trained personnel.

Princeton University,
Princeton, New Jersey

REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS

W. T. Thom, Jr., Chairman

L. H. Adams
N. L. Bowen
W. Bowie
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O. H. Gish
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B. Gutenberg
M. K. Hubbert
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E. S. Larsen
F. W. Lee
C. R. Longwell
J. B. Macelwane
G. R. Mansfield
O. E. Meinzer
L. B. Slichter
H. R. Wanless
B. B. Weatherby

Somewhat over two years ago this Committee began work by undertaking an informal census and review of geophysical-geological studies which were already in progress and which were of such a sort as to be naturally contributory to the objectives which the Committee was created to promote. As this survey progressed, the Committee also began the formulation of an informal but comprehensive statement of objectives--a copy of which was recently transmitted to the National Research Council's Committee on Borderland Fields through Professor Gutenberg.

Because of the near-completion of its general survey and planning activities, the Committee feels that its report this year should consist of a brief statement summarizing what it has accomplished to date, the work it now has in progress, and the activities which it contemplates or recommends for the immediate future.

Work done to date

"Basement-surface" map--In the Committee's comprehensive program of work, one of the immediately important items was the construction of a regional map of the United States showing the configuration of the top of the basement complex--as many geophysical-geological relationships are directly controlled by and descriptive of the depth to and configuration of this surface. A reconnaissance-map and model showing the form of this "basement"-surface was prepared and was, as many will recall, exhibited at the sessions of the American Geophysical Union at Washington in 1936 and also at the Edinburgh Assembly of the International Union of Geodesy and Geophysics.

"Gravity-anomaly" map--A general study showing the regional relation of gravity-anomalies to this basement-structure has also been prepared and has similarly been exhibited both at Washington and at Edinburgh.

"Geothermal", "magnetic", and "epicenter" maps--Likewise, regional compilations of epicentral positions, of temperature-gradient data, and of magnetic-geologic or magnetic-gravitational relationships have also been assembled or prepared--the results of the most recent of these studies being a map which shows that a correlation exists between systematic magnetic and gravitational variations in a large area in southwestern Alabama.

Gravitational study in southern New England--Among pieces of work in which the Committee has been especially interested is one which has been carried out by Professor Longwell, with the cooperation of the United States Coast and Geodetic Survey. In this study, gravity-stations have been run in east-west profiles across southern New England, revealing highly significant geological conditions which have been described and discussed by Professor Longwell in a paper soon to be published by the Geological Society of America.

Gravitational-seismic-geologic profile in Virginia--A similar study in which this Committee has likewise been deeply interested has been the running of a gravitational profile along the landward part of the seismic survey-line followed by Dr. Ewing in his work in the Virginia Coastal Plain-Continental Shelf study. The gravitational anomalies revealed by pendulum-stations on this profile-line or adjacent thereto have been described by C. H. Swick in the Bulletin of the American Association of Petroleum Geologists for March 1937.

Work in progress

Background structural studies--Work in progress includes a continuation of the compilation of the "basement-structures" map--a task which has been greatly facilitated by a grant-in-aid made for the purpose last year by the National Research Council.

As a by-product of this work a regional map showing the near-surface structure of parts of the northwestern Great Plains Region has been forwarded to Professor Longwell (as Chairman of the Tectonics Committee of the Division of Geology and Geography of the National Research Council) for incorporation in that Committee's structural map of the United States.

Background stratigraphic-structural studies--A very important study of the thickness, composition, and structure of the stratified rocks underlying the Illinois coal-basin is being carried out by Professor Wanless, in order to provide such a basis of specific knowledge regarding underground conditions as will make the region thus studied a highly desirable field-laboratory for testing and comparing geophysical instruments and methods against each other and against known geology.

The abundant drill-record information available for the area will prospectively be cast into type-logs, stratigraphic-structural cross-sections, thickness maps for specific formations or groups of formations, and structure contour-maps drawn on a number of selected beds.

"Type-map" collection--Work is also proceeding on the collection of type-maps showing either geophysical depiction of regional geologic conditions or of such detailed geophysical maps of ore-bodies, oil-fields, or dam-, reservoir-, and water-conditions as are now non-confidentially available.

Committee recommendations

After careful consideration, this Committee strongly recommends that certain objectives be set up, toward which approach should be made through and by the Union. These may be classed under the four heads of instruments, test-areas and test-models, geophysical bench-marks, and specific studies.

Instruments--Instruments possessing certain accuracies and flexibilities obviously underlie geophysical exploratory studies relating to crustal conditions, and it is most important that thoroughly satisfactory instruments be available before work is done rather than after.

The cause of gravimetric studies practically requires that gravimeters be obtained by construction or otherwise, in order that both first- and second-order work can be rapidly and accurately gotten.

An automobile radio suitable for the detection of faults and steeply inclined contacts, such as has been described by Cloos, also needs to be developed and made available in adequate numbers.

Further testing and possible adaptation of magnetic variometers and of other electrical appliances are indicated as being highly desirable at an early date.

Test-areas and test-models--Through work already done, many areas lend themselves very well to field-testing and calibration of geophysical appliances and methods against known geology--thereby providing an actual as well as a theoretical basis for the geological interpretation of geophysical data. Among such test-areas which are especially favorable for one reason or another are:

(1) Certain areas in California which have been intensively studied geophysically by Buwalda and Gutenberg and geologically by Reed and others.
(2) Parts of Wyoming, Montana, and South Dakota in the Black Hills-Yellowstone Region.
(3) The Illinois Coal-Basin Region, which has been studied geologically and geophysically by the Illinois Geological Survey and by various coal- and oil-companies, besides being the subject of Professor Wanless' present stratigraphic-structural study.
(4) The southern New England Region described by Professor Longwell in his paper recently read before the Geological Society of America.
(5) The Atlantic Coastal Plain Region from New Jersey to Georgia in which unusually favorable opportunities for combining geological work with magnetic, seismic, and gravitational study exist--as described by Thom in the Bulletin of the Geological Society of America for March 1937.
(6) The Alabama-Florida Coastal Plain Region in which the deep drilling done for artesian water or oil has provided a very good background for both the gravitational and magnetic studies already made and for the additional work needed to round out these features.

Besides field-study of test-areas, the laboratory "exploration" of large-scale, ideal models would also be exceedingly helpful as providing a basis for tentative geologic "interpretation by inspection" of geophysical "pictures" for regions of unknown geology.

Establishment of geophysical bench-marks--Assuming that adequate instruments are available and satisfactory methods for interpreting geophysical results are in hand, there yet remains the insuring of the scale-comparability of data obtained by different exploratory groups. To insure such comparability, geophysical as well as topographic bench-mark systems are obviously badly needed and should be established at the earliest possible date. This Committee has, consequently, noted with great appreciation and approval the resolution passed unanimously by the Association of American State Geologists at its February, 1937, meeting, which reads as follows:

"The Association of American State Geologists strongly favors the establishment of a nation-wide system of gravity and magnetic bench-marks, and further recommends that the location of all such bench-marks should be determined in consultation with the State geologists of the respective States."

If such bench-mark systems are provided, the voluminous and excellent results of commercially applied geophysics will gradually become available for scientific purposes, if and when it becomes possible to release these field-data without loss of economic advantage to the companies which have done the work.

Work in test-areas--It is highly desirable that the efficacy and significance of the magnetic method, and probably of certain other methods, be thoroughly tested without delay by the conduct of a well-formulated regional program of study in one or more test-areas--which presumably would not otherwise soon be tested in the course of commercial exploration. In this planning and testing, Federal and State agencies and other research-groups may all play very useful and mutually beneficial roles.

Encouragement of amateur study of earthquakes--In conclusion, this Committee wishes to register its hearty concurrence with the resolution being presented by the Section of Seismology, in which the Section voices its appreciation of the splendid work being done by the Eastern Section of the Seismological Society of America in encouraging and assisting with the construction and maintenance of earthquake recording-sets by amateurs, and especially by students of high-school age. Such work (which is in itself an indication of the rapid growth of popular interest in geophysical-geological topics) cannot fail to be both of broad educational interest and of real and direct scientific value through its disclosure of the exact location and nature of the faulting now in progress throughout the United States.

Princeton University,
Princeton, New Jersey

SYMPOSIUM ON THEORETICAL AND OBSERVATIONAL CONSIDERATIONS OF IMPORTANCE TO FURTHER STUDIES OF THE DEPTHS OF THE EARTH

ON THE ESTIMATION OF TEMPERATURES AT MODERATE DEPTHS IN THE CRUST OF THE EARTH

C. E. Van Orstrand
(Published with the approval of the Director, U. S. Geological Survey)

Introduction

The modern deep well makes it possible to determine the temperatures of the rocks to depths exceeding two miles, and the rock-samples obtained at these great depths enable the geologist to estimate the depths to the deeply buried basement-rocks to a rather high degree of precision. The latter estimates are now being supplemented to a certain extent by the precision-measurements of the geophysicist, so that reliable data seem to be assured even in those areas in which the basement rocks are not reached by the drill. With these two sources of information at our disposal--accurate temperature-measurements and reliable estimates or measurements of depths to bed-rock--it should be possible to construct a rather accurate subsurface map showing the temperatures on the boundary-surface between the sedimentaries and the basement floor. In this paper it is proposed chiefly to outline the method of procedure by making some rough calculations of the temperatures at great depths for a few locations in the United States and for one location near Carnarvon, Cape Province, South Africa.

The data of observation

Temperature-records of seven wells that are fairly representative of the distribution of temperatures with depth at various points in the United States are summarized in Table 1.

The observed depths and temperatures are recorded in Table 1. The value of the temperatures at zero-depth is the annual mean temperature of the air either interpolated or tabulated direct from the Weather Bureau volume on "Climatological data of the United States by sections."

In the entries designated "Constants" the calculations for different ranges of depth, 100-1000 feet, 100-2000 feet, and so on, are based on the least-square adjustment of the straight-line equation, $y = (a + bx)$, in which y is the temperature on the Fahrenheit scale and x is the depth in feet. The value of a determined from the interval, 100-1000 feet, is assumed to be the annual mean temperature of the soil just beneath the surface of the ground. For the remaining intervals of the tabulated constants, the value of a is merely the intercept on the temperature-axis. The quantity b is the gradient, °F per foot; 1/b is the reciprocal gradient, feet per °F; r is the probable error of an observation of weight unity; r_a and r_b are the probable errors respectively of values for a and b.

The calculated values in the sixth and eighth columns are based on the constants obtained respectively from the intervals 100-1000 feet and 100 to greatest depth in the well at which an observation was made. As shown also on the diagrams of Figures 1 to 7, the difference between the observed and computed values (columns seven and nine) shows that the temperatures increase more rapidly as the depth increases, that is, a straight line adjusted to the observed temperatures from 100 to 1000 feet falls below the observed values for the greater depths, and the positive differences between the observed and computed values increase with the depth. The series of diminishing values of (1/b) in the section of constants in the Table shows the same result. A rough measure of the deviation of the depth-temperature curves from linearity is given by the probable error r for the different depths.

The annual mean temperature of the soil just beneath the surface of the ground is higher than the annual mean temperature of the air in contact with the soil. This must be true; otherwise, the Earth would not be losing heat as shown by the depth-temperature curves. Ordinarily, the observed excess does not exceed 2° or 3° F except in the oil-fields of southern California where the excess is seldom less than 8° or 10° F. On account of slight irregularities in the upper part of some of the wells and errors in the interpolated values of the annual mean temperatures of the air, the excess sometimes appears with a positive instead of a negative sign; nevertheless, the value of the annual mean temperature of the air at the location is an indispensable check on the general trend of the upper part of the depth-temperature curve.

Table 1--Observed temperatures in some wells of great depth

Well	Depth		Observed temperatures		Computed temp.	Obs'd minus comp.	Computed temp.	Obs'd minus comp.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Meters	feet	°C	°F	°F	°F	°F	°F
Kern Dodge, Morris Building,					100-1000 feet		100-6500 feet	
Philadelphia, Pennsylvania.	0.0	0	7.8	46.0	46.7	- 0.7	42.7	+3.3
Menoher Highway about 10 miles	30.5	100	8.9	48.0	47.7	+ 0.3	44.0	+4.0
southwest of Johnstown, Pennsylvania,	152.4	500	10.4	50.7	51.3	- 0.6	49.3	+1.4
Just west of the summit	304.8	1000	13.4	56.2	55.9	+ 0.3	55.8	+0.4
of Laurel Hill, Westmoreland	457.2	1500	16.7	62.1	60.5	+ 1.6	62.4	-0.3
County. Elevation, 2721 feet.	609.6	2000	20.6	69.1	65.1	+ 4.0	68.9	+0.2
	762.0	2500	23.9	75.0	69.7	+ 5.3	75.5	-0.5
	914.4	3000	27.2	80.9	74.3	+ 6.6	82.1	-1.2
	1066.8	3500	30.1	86.1	78.9	+ 7.2	88.6	-2.5
	1219.2	4000	33.0	91.4	83.5	+ 7.9	95.2	-3.8
	1371.6	4500	36.2	97.2	88.1	+ 9.1	101.8	-4.6
	1524.0	5000	41.0	105.8	92.7	+13.1	108.3	-2.5
	1676.4	5500	45.7	114.2	97.3	+16.9	114.9	-0.7
	1828.8	6000	51.3	124.3	101.9	+22.4	121.5	+2.8
	1981.2	6500	57.4	135.3	106.5	+28.8	128.0	+7.3
Constants for	a	b		1/b	r	r_a	r_b	
100-1000 feet	46.73	0.00919		108.8	±0.50	±0.50	±0.00078	
100-2000 feet	45.78	0.01121		89.2	±0.72	±0.58	±0.00047	
100-3000 feet	45.40	0.01171		85.4	±0.62	±0.43	±0.00024	
100-4000 feet	45.57	0.01157		86.5	±0.55	±0.34	±0.00014	
100-5000 feet	45.28	0.01176		85.1	±0.68	±0.39	±0.00013	
100-6000 feet	43.84	0.01256		79.6	±1.55	±0.82	±0.00023	
100-6500 feet	42.70	0.01313		76.2	±2.22	±1.13	±0.00030	
100-4500 feet	45.64	0.01152		86.9	±0.52	±0.31	±0.00012	
4500-6500 feet	11.19	0.01894		52.8	±0.71	±2.50	±0.00045	
Cromwell-Franklin Oil Co., Trosper Park No. 5, NE NW, NE sec.					100-1000 feet		100-6000 feet	
13, T.11 N., R.3 W., Oklahoma	0.0	0	15.4	59.8	57.4	+ 2.4	54.7	+5.1
County, Oklahoma (Oklahoma	30.5	100	14.5	58.1	58.2	- 0.1	55.8	+2.3
City). Elevation, 1254 feet	152.4	500	16.6	61.8	61.6	+ 0.2	60.5	+1.3
(approximately). Last entry at	304.8	1000	18.7	65.6	65.7	- 0.1	66.3	-0.7
depth of 1828.8 meters resulted	457.2	1500	22.2	72.0	69.9	+ 2.1	72.1	-0.1
from duplicate test with a dif-	609.6	2000	25.1	77.2	74.0	+ 3.2	77.9	-0.7
ferent set of thermometers.	762.0	2500	28.1	82.6	78.2	+ 4.4	83.7	-1.1
	914.4	3000	31.8	89.3	82.3	+ 7.0	89.5	-0.2
	1066.8	3500	34.5	94.1	86.5	+ 7.6	95.3	-1.2
	1219.2	4000	37.1	98.7	90.6	+ 8.1	101.1	-2.4
	1371.6	4500	40.9	105.6	94.8	+10.8	106.9	-1.3
	1524.0	5000	44.6	112.3	98.9	+13.4	112.7	-0.4
	1676.4	5500	48.6	119.5	103.1	+16.4	118.5	+1.0
	1828.8	6000	53.2	127.8	107.2	+20.6	124.3	+3.5
	1828.8	6000	53.2	127.8	107.2	+20.6	124.3	+3.5
Constants for	a	b		1/b	r	r_a	r_b	
100-1000 feet	57.40	0.00830		120.4	±0.17	±0.17	±0.00026	
100-2000 feet	56.64	0.01010		99.0	±0.50	±0.41	±0.00033	
100-3000 feet	56.13	0.01073		93.2	±0.59	±0.41	±0.00023	
100-4000 feet	56.14	0.01073		93.2	±0.52	±0.53	±0.00014	
100-5000 feet	55.67	0.01105		90.5	±0.63	±0.36	±0.00012	
100-6000 feet	54.67	0.01161		86.2	±1.14	±0.60	±0.00017	
4000-6000 feet	40.68	0.01442		69.3	±0.38	±1.21	±0.00025	

The curves represented on Figures 5 and 6 are anomalous. The flat segment in Figure 5 is probably the result of convection in water which may be limited to the well itself despite the fact that there are large openings in the lava-beds through which the well penetrates. The concave form of the curve shown in Figure 6 is the result of a very small discharge of gas. The true curve probably bends upward beneath the straight line shown in the Figure and passes a few degrees below the observed value of 241°.2 F at 9000 feet.

Table 1--Observed temperatures in some wells of great depth--Continued

Well	Depth		Observed temperatures		Computed temp.	Obs'd minus comp.	Computed temp.	Obs'd minus comp.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Meters	feet	°C	°F	°F	°F	°F	°F
George F. Getty Oil Co., Dooley					100-1000 feet		100-6000 feet	
No. 7, Sec. 24, T.20 S., R.29	0.0	0	16.7	62.1	66.0	- 3.9	63.4	-1.3
E., New Mexico Meridian, Eddy	30.5	100	18.9	66.1	66.5	- 0.4	64.1	+2.0
County, New Mexico (Carlsbad).	76.2	250	19.8	67.7	67.3	+ 0.4	65.3	+2.4
Elevation, 3309 feet; depth on	152.4	500	20.4	68.9	68.7	+ 0.2	67.2	+1.7
April 24, 1936, 6683 feet.	228.6	750	21.1	70.0	70.1	- 0.1	69.1	+0.9
	304.8	1000	21.8	71.3	71.4	- 0.1	71.0	+0.3
	457.2	1500	23.2	73.9	74.1	- 0.2	74.8	-0.9
	609.6	2000	25.3	77.5	76.9	+ 0.6	78.6	-1.1
	762.0	2500	27.3	81.1	79.6	+ 1.5	82.3	-1.2
	838.2	2750	28.6	83.5	81.0	+ 2.5	84.2	-0.7
	914.4	3000	29.6	85.2	82.3	+ 2.9	86.1	-0.9
	990.6	3250	30.3	86.6	83.7	+ 2.9	88.0	-1.4
	1066.8	3500	30.9	87.6	85.0	+ 2.6	89.9	-2.3
	1219.2	4000	33.2	91.7	87.8	+ 3.9	93.7	-2.0
	1371.6	4500	35.7	96.2	90.5	+ 5.7	97.5	-1.3
	1524.0	5000	38.8	101.8	93.2	+ 8.6	101.3	+0.5
	1676.4	5500	41.3	106.3	95.9	+10.4	105.1	+1.2
	1828.8	6000	44.3	111.8	98.7	+13.1	108.9	+2.9
Constants for	a	b		1/b	r	r_a	r_b	
100-1000 feet	65.97	0.00545		183.5	±0.24	±0.18	±0.00024	
100-2000 feet	65.85	0.00565		177.0	±0.25	±0.16	±0.00015	
100-3000 feet	65.34	0.00640		156.3	±0.43	±0.23	±0.00013	
100-4000 feet	65.24	0.00649		154.0	±0.40	±0.20	±0.00009	
100-5000 feet	64.66	0.00691		144.6	±0.73	±0.34	±0.00012	
100-6000 feet	63.37	0.00759		131.8	±1.12	±0.49	±0.00015	
4000-6000 feet	51.26	0.01006		99.4	±0.21	±0.68	±0.00013	
Johnson No. 1, The A. A. Rolle-					100-1000 feet		100-6500 feet	
stone Co., SW 1/4, sec. 34, T.2	0.0	0	8.7	47.6	56.0	- 8.4	50.7	+3.1
N., R.69 W., Boulder County,	30.5	100	14.5	58.1	57.7	+ 0.4	53.1	+5.0
Colorado (about 5 miles south	152.4	500	17.9	64.2	64.8	- 0.6	62.7	+1.5
of Longmont). Elevation, 4950	304.8	1000	23.3	74.0	73.7	+ 0.3	74.7	-0.7
feet (approximately); total	457.2	1500	29.2	84.6	82.6	+ 2.0	86.7	-2.1
depth, 7300 feet; extrapolated	609.6	2000	35.7	96.2	91.5	+ 4.7	98.7	-2.5
boiling point at 6565 feet.	914.4	3000	48.8	119.9	109.2	+10.7	112.7	-2.8
	1219.2	4000	62.7	144.9	127.0	+17.9	146.7	-1.8
	1981.2	6500	99.1	210.3	171.3	+39.0	206.7	+3.6
Constants for	a	b		1/b	r	r_a	r_b	
100-1000 feet	55.97	0.01775		56.4	±0.53	±0.54	±0.00083	
100-2000 feet	54.84	0.02018		49.6	±0.80	±0.64	±0.00052	
100-3000 feet	53.78	0.02152		46.5	±1.16	±0.81	±0.00049	
100-4000 feet	52.80	0.02251		44.4	±1.43	±0.91	±0.00042	
100-6500 feet	50.74	0.02399		41.7	±2.18	±1.19	±0.00039	
Langell Valley Oil Co., Langell					100-375 feet		375-2125 feet	
Valley well No. 1, NE corner	0.0	0	8.7	47.7	48.0	-0.3		
SW NE sec. 19, T.39 S., R.12	30.5	100	12.2	54.0	53.7	+0.3		
E., Klamath County, Oregon	76.2	250	16.4	61.6	62.3	-0.7		
(about 4 miles east of Bonanza).	114.3	375	21.0	69.8	69.4	+0.4	69.8	0.0
Lava from surface to 4365 feet,	152.4	500	21.1	69.9	....	...	69.8	+0.1
the last depth from which rock-	228.6	750	21.1	69.9	....	...	69.9	0.0
samples have been received;	304.8	1000	21.2	70.1	....	...	70.1	0.0
from 3327-3930 feet there is	457.2	1500	21.2	70.1	....	...	70.3	-0.2
trace of gas; water-bed is at	609.6	2000	21.3	70.3	....	...	70.6	-0.3
3380-3390 feet.	628.5	2062	21.3	70.4	....	...	70.6	-0.2
	638.0	2093	21.6	70.8	....	...	70.6	+0.2
	647.7	2125	21.7	71.0	....	...	70.6	+0.4

Table 1--Observed temperatures in some wells of great depth--Continued

Well	Depth		Observed temperatures		Computed temp.	Obs'd minus comp.	Computed temp.	Obs'd minus comp.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Meters	feet	°C	°F	°F	°F	°F	°F
Langell Valley well No. 1--					100-375 feet		2250-3870 feet	
Continued.	685.8	2250	23.8	74.9	....	...	71.6	+3.3
	762.0	2500	31.6	88.8	....	...	92.0	-3.2
	838.2	2750	41.7	107.2	....	...	112.3	-5.1
	914.4	3000	57.3	135.1	....	...	132.6	+2.5
	952.5	3125	62.2	144.6	....	...	142.8	+1.8
	990.6	3250	67.3	153.1	....	...	153.0	+0.1
	1030.2	3380	73.8	164.8	....	...	163.5	+1.3
	1066.8	3500	79.2	174.5	....	...	173.3	+1.2
	1143.0	3750	90.1	194.2	....	...	193.6	+0.6
	1179.6	3870	93.8	200.9	....	...	203.4	-2.5
Constants for	a	b		1/b	r	r_a	r_b	
100-375 feet	47.97	0.05723		17.5	±0.58	±0.79	±0.00298	
375-2125 feet	69.57	0.000495		2021.4	±0.16	±0.12	±0.00008	
2250-3870 feet	111.39	0.08134		12.3	±1.94	±3.92	±0.00123	
Berry No. 1, General Petroleum					100-1000 feet		100-9000 feet	
Corporation of California, NE	0.0	0	18.1	64.6	76.8	-12.2	80.1	-15.5
SE SE sec. 30, T.28 S., R.21	30.5	100	26.2	79.2	78.5	+ 0.7	82.0	-2.8
E., Kern County, California	76.2	250	27.2	81.0	81.0	0.0	84.8	-3.8
(about 40 miles west of Bakers-	152.4	500	29.0	84.2	85.2	- 1.0	89.5	-5.3
field). Elevation, 680 feet;	228.6	750	31.7	89.0	89.5	- 0.5	94.2	-5.2
small flow of gas; interpolated	304.8	1000	34.7	94.5	93.7	+ 0.8	98.9	-4.4
boiling point at 6872 feet;	381.0	1250	38.8	101.8	97.9	+ 3.9	103.7	-2.1
total depth, 11,377 feet; well	457.2	1500	42.5	108.5	102.1	+ 6.4	108.4	+0.1
filled to top with oil, mud,	609.6	2000	48.4	119.2	110.6	+ 8.6	117.8	+1.4
and water; readings at 8860 and	762.0	2500	54.3	129.8	119.1	+10.7	127.3	+2.5
9000 feet are probably too	914.4	3000	60.1	140.2	127.5	+12.7	136.7	+3.5
high.	1066.8	3500	65.9	150.7	136.0	+14.7	146.1	+4.6
	1219.2	4000	71.8	161.2	144.4	+16.8	155.6	+5.6
	1371.6	4500	77.1	170.8	152.9	+17.9	165.0	+5.8
	1524.0	5000	82.5	180.5	161.3	+19.2	174.4	+6.1
	1676.4	5500	87.8	190.1	169.8	+20.3	183.9	+6.2
	1828.8	6000	92.4	198.3	178.2	+20.1	193.3	+5.0
	1981.2	6500	96.9	206.5	186.7	+19.8	202.7	+3.8
	2133.6	7000	101.1	213.9	195.1	+18.8	212.2	+1.7
	2286.0	7500	105.4	221.8	203.6	+18.2	221.6	+0.2
	2438.4	8000	109.4	228.9	212.1	+16.8	231.0	-2.1
	2590.8	8500	113.0	235.4	220.5	+14.9	240.5	-5.1
	2700.5	8860	115.6	240.1	226.6	+13.5	247.3	-7.2
	2743.2	9000	116.2	241.2	229.0	+12.2	249.9	-8.7
Constants for	a	b		1/b	r	r_a	r_b	
100-1000 feet	76.79	0.01691		59.1	±0.60	±0.51	±0.00082	
100-2000 feet	74.69	0.02175		46.0	±1.17	±0.75	±0.00068	
100-3000 feet	74.59	0.02191		45.6	±1.01	±0.55	±0.00035	
100-4000 feet	74.76	0.02173		46.0	±0.94	±0.46	±0.00022	
100-5000 feet	75.19	0.02137		46.8	±0.97	±0.44	±0.00016	
100-6000 feet	75.83	0.02094		47.8	±1.18	±0.50	±0.00016	
100-7000 feet	76.85	0.02035		49.1	±1.71	±0.68	±0.00018	
100-8000 feet	78.08	0.01974		50.7	±2.31	±0.88	±0.00020	
100-9000 feet	80.08	0.01887		53.0	±3.24	±1.17	±0.00023	

Local variations of temperature

Observations in some of the oil-fields show that the temperatures at the same depth are highest over the tops of the domes or anticlinal structures. Excellent examples of this kind of horizontal distribution of temperatures have been found at Lance Creek, Salt Creek, Thermopolis, and Lost Soldier, Wyoming; at Homer, Louisiana; at Garber, Oklahoma; at Big Lake, Texas; at Long

Table 1--Observed temperatures in some wells of great depth--Concluded

Well (1)	Depth (2)	Depth (3)	Observed temperatures (4)	Observed temperatures (5)	Computed temp. (6)	Obs'd minus comp. (7)	Computed temp. (8)	Obs'd minus comp. (9)
	Meters	feet	°C	°F	°F	°F	°F	°F
Nesa No. 11, Shell Oil Co., about 350 feet north on Dawson Street and 60 feet west on 23d Street, Los Angeles County, California (Signal Hill, Long Beach). Elevation, 339 feet; depth, 9280 feet; 5-3/4 inch casing to 9144 feet; hole full of water with a little oil on top; gas pressure varied during test from 80 to 40 pounds per sq. inch; line run through packer; interpolated boiling point, 7239 feet. Last entry at depth 2743.2 meters resulted from duplicate test.					100-1000 feet		100-9000 feet	
	0.0	0	16.0	60.8	69.7	-8.9	67.3	-6.5
	30.5	100	21.9	71.4	71.6	-0.2	69.3	+2.1
	152.4	500	26.4	79.5	79.1	+0.4	77.2	+2.3
	304.8	1000	31.3	88.4	88.6	-0.2	87.1	+1.3
	457.2	1500	35.7	96.2	98.0	-1.8	97.1	-0.9
	457.2	1500	35.7	96.2	98.0	-1.8	97.1	-0.9
	609.6	2000	41.2	106.1	107.4	-1.3	107.0	-0.9
	762.0	2500	45.8	114.5	116.8	-2.3	116.9	-2.4
	914.4	3000	51.5	124.7	126.2	-1.5	126.8	-2.1
	1066.8	3500	57.1	134.8	135.7	-0.9	136.7	-1.9
	1219.2	4000	63.4	146.1	145.1	+1.0	146.7	-0.6
	1371.6	4500	68.9	156.1	154.5	+1.6	156.6	-0.5
	1524.0	5000	74.6	166.3	163.9	+2.4	166.5	-0.2
	1676.4	5500	80.4	176.7	173.4	+3.3	176.4	+0.3
	1828.8	6000	85.7	186.2	182.8	+3.4	186.4	-0.2
	1981.2	6500	92.1	197.8	192.2	+5.6	196.3	+1.5
	2133.6	7000	97.5	207.5	201.6	+5.9	206.2	+1.3
	2286.0	7500	102.7	216.9	211.0	+5.9	216.1	+0.8
	2438.4	8000	108.2	226.8	220.5	+6.3	226.1	+0.7
	2590.8	8500	113.5	236.3	229.9	+6.4	236.0	+0.3
	2743.2	9000	118.3	245.0	239.3	+5.7	245.9	-0.9
	2743.2	9000	118.4	245.1	239.3	+5.8	245.9	-0.8

Constants for	a	b	1/b	r	r_a	r_b
100-1000 feet	69.72	0.01884	53.1	±0.33	±0.34	±0.00052
100-2000 feet	70.04	0.01792	55.8	±0.41	±0.33	±0.00027
100-3000 feet	69.90	0.01807	55.3	±0.42	±0.30	±0.00016
100-4000 feet	69.10	0.01877	53.3	±0.77	±0.48	±0.00020
100-5000 feet	68.40	0.01927	51.9	±0.94	±0.53	±0.00018
100-6000 feet	67.91	0.01954	51.2	±0.96	±0.50	±0.00014
100-7000 feet	67.36	0.01981	50.5	±1.06	±0.52	±0.00013
100-8000 feet	67.19	0.01988	50.3	±1.00	±0.46	±0.00010
100-9000 feet	67.28	0.01985	50.4	±0.95	±0.42	±0.00008
4000-9000 feet	66.70	0.01997	50.07	±0.55	±0.70	±0.00010

Beach, California; and at several other fields [see 1 of "References" at end of paper]. In some of the fields, the evidence is not conclusive, but these partial failures are certainly due in many instances to disturbed conditions which result from drilling and producing operations. The Salt Creek Field, for example, was mapped before big-scale production was begun, but subsequent observations have shown that the temperatures as they exist today could not be correlated with structure.

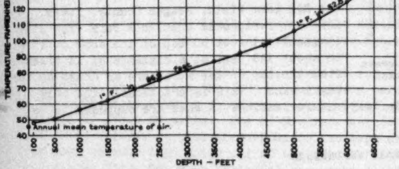

FIG. 1—DEPTH-TEMPERATURE CURVE; KERN DODGE, ABOUT 10 MILES SOUTHWEST OF JOHNSTON, PENNSYLVANIA

In Figure 8, the closed broken lines represent elevations on the Second Wall Creek Sand. Faults are represented by broken lines that intersect the contours. The small discs represent locations of wells and the accompanying numbers represent the depths at which a temperature of 80° F is reached. The heavy continuous lines represent contours on the 80° F isogeothermal surface. The reciprocal gradients for the first 1000 feet in this field vary from less than 30 feet per degree F on top of the structure to 67 feet per degree F at the lowest observed point on the flank. Observations in the synclinal area around

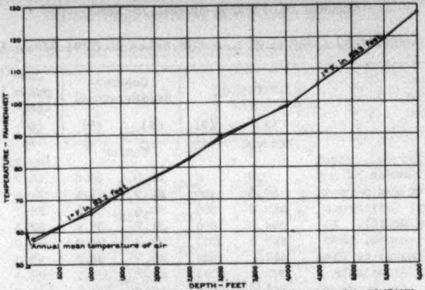

FIG. 2—DEPTH-TEMPERATURE CURVE; CROMWELL-FRANKLIN OIL COMPANY, TROSPER PARK NO. 5, OKLAHOMA CITY, OKLAHOMA

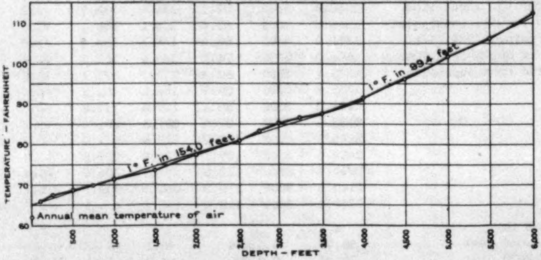

FIG. 3—DEPTH-TEMPERATURE CURVE; GEORGE F. GETTY OIL COMPANY, DOOLEY NO. 7, ABOUT 20 MILES NORTHEAST OF CARLSBAD, NEW MEXICO

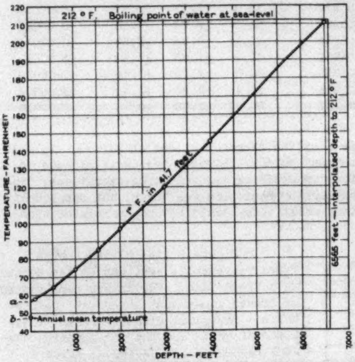

FIG. 4—DEPTH-TEMPERATURE CURVE; A.A. ROLLESTONE COMPANY, JOHNSON NO. 1, ABOUT 9 MILES SOUTH OF LONGMONT, COLORADO

the dome would probably show reciprocal gradients that greatly exceed 67 feet per degree F.

The configuration of the contours in the Salt Creek Field suggests basement granite as the chief source of the heat. That this is the correct explanation was amply demonstrated by the Stanolind Oil and Gas Company's deep well, No. 29-Tp, which reached the granite at a depth of 5420 feet. The well is located in the center of the SW 1/4, NW 1/4, Sec. 35, T.40 N., R.79 W., Natrona County, Wyoming.

Another well-defined correlation between temperature and structure is shown in Figure 9 which represents the temperatures at a depth of 2800 feet on the structure-map of the Big Lake Field, Reagan County, Texas. Here the reciprocal gradients vary from 1° F in about 111 feet on top of the dome to 1° F in about 148 feet at a distance of 14 miles from the top of the structure as drawn on the Texon sand. This is practically the only field in which it has been possible to obtain temperature-readings in what are supposed to be synclines adjacent to the domes [2].

Regional variations

An important contribution to the subject of regional variations was made in 1920 by Dr. N. H. Darton [3]. His map of eastern South Dakota and southeastern North Dakota shows that the

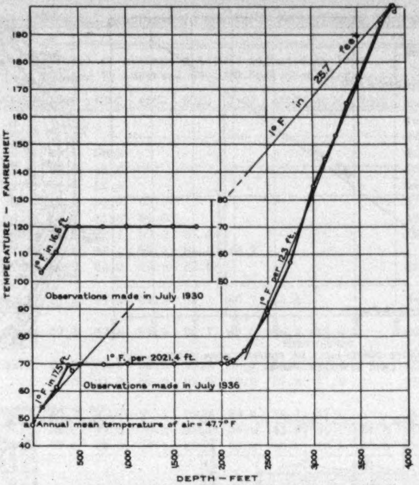

FIG. 5—DEPTH-TEMPERATURE CURVE; LANGELL VALLEY OIL COMPANY, LANGELL VALLEY NO. 1, ABOUT 4 MILES EAST OF BONANZA, OREGON

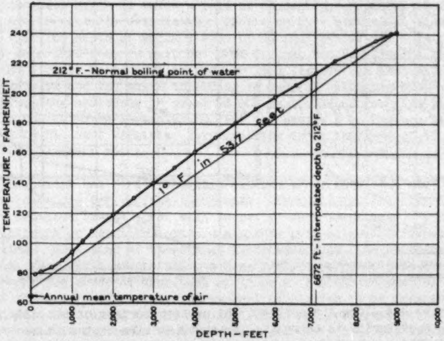

FIG. 8—DEPTH-TEMPERATURE CURVE; GENERAL PETROLEUM CORPORATION OF CALIFORNIA, BERRY NO. 1, ABOUT 40 MILES WEST OF BAKERSFIELD, CALIFORNIA

temperatures rise as the depth to the granite diminishes in passing southward through the southeastern part of South Dakota into northeastern Nebraska.

In 1930, John A. McCutchin [4], observer for the American Petroleum Institute in the State of Oklahoma, showed that the 100° F isogeotherm paralleled roughly the basement floor from Sapulpa to Oklahoma City, a distance of about 90 miles, and also from Wewoka to Oklahoma City, a distance of about 60 miles. One of Mr. McCutchin's sections is reproduced in Figure 10. Dr. N. W. Bass informs me that the depths to the tops of the structures near Sapulpa probably vary from 3000 to 4000 feet while off of the structure his estimated depths are 4000 to 5000 feet. At Oklahoma City, Dr. Bass estimates the depth to the basement beneath the structure to be something like 7000 feet; and 10,000 feet in the syncline.

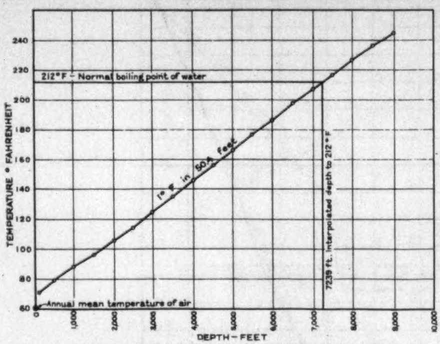

FIG. 7—DEPTH-TEMPERATURE CURVE; SHELL OIL COMPANY, NESA 11, SIGNAL HILL, LONG BEACH, CALIFORNIA

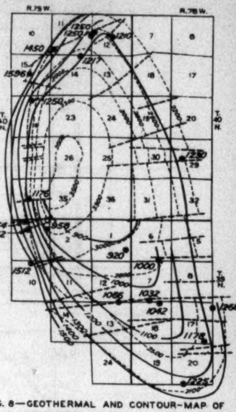

FIG. 8—GEOTHERMAL AND CONTOUR-MAP OF SALT CREEK DOME, NATRONA COUNTY, WYOMING

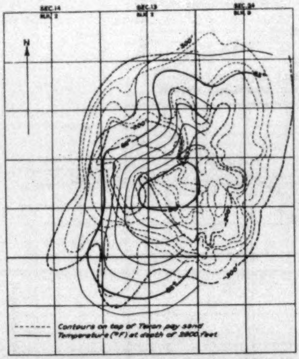
SEC.14
SEC.13
SEC.24
N
Contours on top of Texon pay sand
Temperature (°F) at depth of 2800 feet

FIG. 9—GEOTHERMAL AND CONTOUR-MAP OF THE BIG LAKE FIELD, REAGAN COUNTY, TEXAS

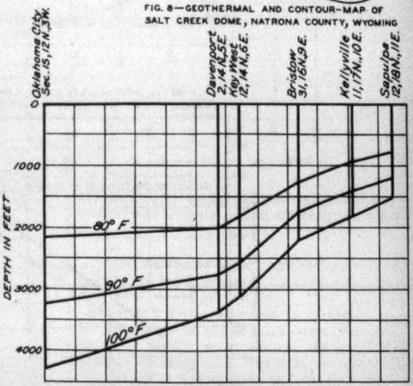

FIG. 10—ISOGEOTHERMAL SURFACES, CENTRAL OKLAHOMA

Observations in and along the northern and western borders of the deep Appalachian trough afford an unusual opportunity to correlate temperatures with depths to bed-rock. Table 2 contains the results from a selected list of tests that I have made at 13 locations in this area during the past few years. The numbers represent feet per degree F and are the result of taking the reciprocal of the average gradient obtained by adjusting a straight line by the method of least squares through all of the observed points in the interval of 1000 feet preceding the tabular number at the top of the column. Thus, 50.1 is obtained by using all of the observations between 750 and 1750 feet; similarly, the number 58.5 is the reciprocal of the average gradient obtained by adjusting all of the observations from 2000 to 3000 feet, inclusive; and so on.

Table 2 shows that the temperatures in the Oriskany sand increase somewhat irregularly with the depth of the sand; and furthermore, the numbers in the vertical columns likewise increase rather definitely with the depth to the sand. These results show that the lowest temperatures are to be expected in the deep syncline. Additional evidence on this point is to be found in Figure 11 which is an enlarged reproduction of the eastern portion of the map by Dr. W. T. Thom, Jr., [5], showing the approximate configuration of the surface of the basement crystallines. The small discs on the map represent well-locations and the numbers alongside of the discs refer to

Table 2--Reciprocal geothermal gradients in New York, Pennsylvania, and West Virginia

No.	County	State	Reciprocal of average gradient adjusted by least squares in interval of 1000 feet preceding									Depth to Oriskany	Temp. of Oriskany	Elevation of well
			3000	3500	4000	4500	5000	5500	6000	6500	7000			
												feet	°F	feet
1	Schuyler	N.Y.	50.1[a]									1761	81.3	1232
2	Steuben	N.Y.	58.5	57.1	56.2							4255	115.9	1792
3	Wood	W.Va.	63.0	60.0	56.8							4531	119.0	1256
3	Wood	W.Va.	61.0	59.5	55.6							4420	118.3	1216
4	Alleghany	N.Y.	62.1	53.2	52.9	46.3						4754	127.0	2092
5	Butler	Pa.	56.5	51.8	50.3	50.0						4809	124.6	1180
6	Potter	Pa.	66.2	54.9	52.1	50.0	47.2					5165	131.1	2106
7	Tioga	Pa.	63.6	52.4	52.1	59.2	52.3	46.7				....	.....	1300
8	Potter	Pa.	67.6	59.9	51.0	49.5	52.9					5287	131.5	2156
9	Westmoreland	Pa.	64.9	67.6	67.6	64.5	54.1	46.7	44.8			6822	166.7	1116
9	Westmoreland	Pa.	69.4	67.1	67.6	61.6	50.7	48.5	46.9	48.6		6822	166.3	1122
9	Westmoreland	Pa.	81.3	81.3	68.5	59.5	58.5	59.2	54.6	52.4		6822	155.7	1128
10	Doddridge	W.Va.	....	80.6	81.0	69.0	59.9	62.5	57.8	47.8		6960	152.7	1138
11	Westmoreland	Pa.	84.7	90.1	95.2	90.1	69.4	58.8	54.1	47.4		7000	146.2	2721
12	Marion	W.Va.	74.0	88.0	77.9	70.6	61.1	46.9	43.7	46.7	54.3	7018	162.6	1201
13	Harrison	W.Va.	78.6	77.5	80.0	74.1	69.4	65.8	55.2	46.9	46.5	7416	161.1	1164

[a] At 1750 feet.

the numbers in the first column of Table 2 in which the sequence of natural numbers corresponds approximately to the increased depth at which a rate of 50 feet per degree F is reached as shown by the series of somewhat irregularly diminishing numbers on each horizontal line. The Table and map together show that the depth at which a rate of 50 feet per degree F is reached increases more or less uniformly from 1750 feet in well No. 1 at Tyrone, New York, where the depth to the crystallines is about 8500 feet, to a depth of 7000 or 7500 feet in the deep syncline near Fairmont, West Virginia, wells 12 and 13, where according to careful estimates by Dr. G. B. Richardson the total thickness of the sediments is about 26,000 feet. Hence there is a range of more than one mile in the depths at which a rate of 50 feet per degree F is reached as we pass from Tyrone, New York, to Fairmont, West Virginia, corresponding to an increase of 17,000 or 18,000 feet in the depths to the basement rocks.

In all of the wells except the first, the observations above 2000 feet were rejected in order to eliminate the corrections for surface-topography. Fortunately, the correction for surface topography at the location of the first well is not of much importance. Other sources of error are neglect of location on structure which diminishes gradually with increasing depths, and errors of observation. When some of these deep tests were made, the technique of obtaining accurate observations at such great depths had not been fully developed; consequently, it is to be expected that errors of the order of magnitude of 1° or 2° F occur in some of the readings. Notwithstanding all of these irregularities, the general conclusion to be deduced from the entire set of observations is that the depths to the basement floor are reflected in the temperature-readings at the upper levels in the sense that the temperatures rise as the depths to the crystalline rocks diminish.

Relation of temperature-gradients to gravity-anomalies

In the Transactions of last year, Dr. G. P. Woollard [6] made an interpretation of gravity-anomalies with reference to local and geologic structure in which he reached the conclusion that there is a definite relationship between gravity and geologic structure, and that in general the gravity-profile represents the configuration of the crystalline basement--when the crystallines are exposed at the surface there is a "high" on the gravity-profile and when they are deeply buried under light detrital material there is a "low" on the gravity-profile. This conclusion implies an obvious correlation with temperatures, namely, high temperatures and positive gravity-anomalies stand in a definite relation to each other.

Dr. Woollard states that certain modifications of the general statement that gravity-

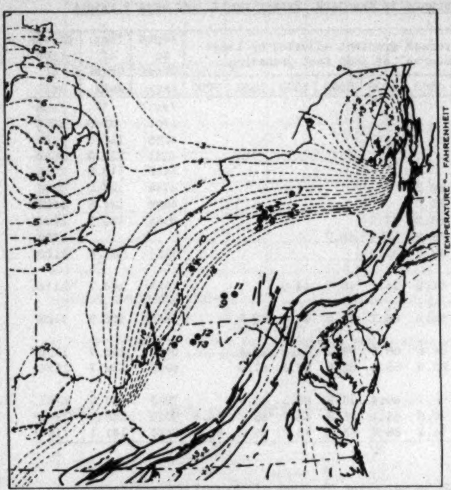

FIG. 11—LOCATIONS OF WELLS AND DEPTHS TO CRYSTALLINE ROCKS

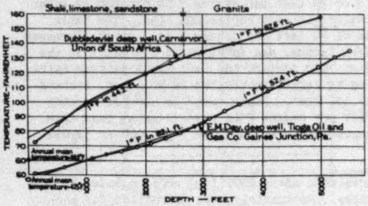

FIG. 13—DEPTH-TEMPERATURE CURVES IN SEDIMENTS AND CRYSTALLINES

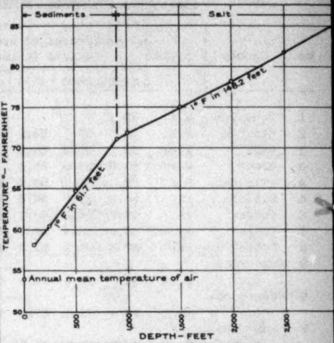

FIG. 12—DEPTH-TEMPERATURE CURVE; UTAH SOUTHERN OIL COMPANY, BALSLEY NO. 1, ABOUT 15 MILES SOUTHEAST OF THOMPSONS, GRAND COUNTY, UTAH

anomalies are negative in a synclinal basin must be made under certain circumstances, as for example, when a basin is filled with sediments of high density. The corresponding effect on the temperatures in the basin would be to lower them so that the contrast between the high and the low temperatures would be intensified. On the other hand, if the basin be filled with loose sedimentary material containing a minimum amount of moisture, the temperature-gradients would be greatly increased, perhaps to the point of neutralizing the difference between the "highs" and the "lows." Results of this kind are not surprising when the complexity of the Earth's crust is taken into account. It is to be expected that other anomalies will be found. The true explanation in each case is to be found in superposing the anomaly on the fundamental postulate that in general the temperatures of rock at moderate depths are controlled largely by the depths to the basement rocks.

The part played by uplift, subsidence, and erosion in the present-day distribution of temperatures in the rocks is of deep concern to the geophysicist. Jeffreys [7] estimates a rise of 250° C during subsidence to a depth of 10 kilometers in 130 million years. With sufficient time, the temperature-gradient would again return to normal, but uplift and erosion must tend always to steepen the gradient at the surface. To what extent these operations are reflected in the temperatures of the rocks is not definitely known except that in areas that have been static for something like 200 million years, the Permian Basin, for example, the temperatures are low, while in areas of recent uplift, such as are found in Wyoming and southern California, the temperatures are uniformly high. The time-factor has no counterpart in gravimetric problems, but the distribution of "highs" and "lows" in these areas of recent uplift will again be controlled by the basement floor so that our fundamental hypothesis of the dependence of both high temperatures and positive gravity-anomalies on depths to the basement rocks is probably the best working hypothesis that can be formulated at this time.

Extrapolation to moderate depths

Important contributions to the subject of temperatures at both moderate and great depths have been made by Jeffreys [8], Adams [9], Holmes [10], and Daly [11]. Professor Daly [12] believes that for petrology the temperatures to a depth of 100 km is the most vital problem connected with the thermal energy of the globe.

It is not my purpose to attempt an improvement on existing estimates. Instead, I propose to ascertain to what extent the data of actual observation can be used to estimate the temperatures to a depth of 100 km.

From the discussion given in this paper, it is obvious that the use of gradients at ordinary depths in domes and anticlines will give temperatures that are too high at great depths. The isotherms over a dome or an anticline flatten with increased depth to a certain level where the distinction between anticlines and synclines is lost. This level is undoubtedly at a very great depth so that an error appears at once in any attempt to extend the depth-temperature curves to the lower levels.

Under these circumstances, the nearest approach that can be made to a correct extrapolation of the observed depth-temperature curve is to extend the curve from its lowest point using the observed temperature and the calculated gradient at that point. Extension of the curves to the base of the sediments can be carried out with a reasonable degree of accuracy, due very largely, of course, to the fact that very deep tests are now available.

Ordinarily, the sharp change in trend of the depth-temperature curves at the surface of contact between two different formations does not correspond to what one would expect from tests in the laboratory. Instead of the sharp intersections indicated by the differences in the coefficients of conductivity, the curves change gradually from one trend to another as the result probably of moisture in the rocks. Figure 12 shows an exception. Here the plane of contact of the sediment with the salt is indicated accurately by the depth-temperature curve. The reduction in the gradient at the top of the salt is 0.58 of the original gradient.

In Figure 13 are shown two curves in which the usual rounded appearance of the curves is very conspicuous. The increase in the gradient in the Pennsylvania well amounts to 0.64 and the decrease in the Carnarvon well is 0.465 of the original gradient.

Table 3 contains original temperature-data taken from the seven well-records contained in Table 1 and, in addition, the data for the Tyrone Well in New York and the Carnarvon Well in South Africa. Estimates of temperature at the bottom of the sediments are given in the second horizontal line from the bottom and are based on the numbers in the Table preceding the tabulations. The numbers in the last horizontal line are assumed to be the reciprocal gradients in the crystallines and are the reciprocals of the gradients that are equal to the original gradient less 0.465 times the original gradient. This ratio of 0.465 certainly does not hold for all sediments and basement rocks in contact, but it is probably the only measured value that has been published.

Table 4 is based on the estimated temperatures and reciprocal gradients at the tops of the basement rocks as recorded in the last two horizontal lines of Table 3. There is given in addition the values calculated by Jeffreys, Adams, Holmes, and Daly. The agreement between the calculations down to a depth of about 60 km is much better than expected. From 60 to 100 km the temperature computed from the extension of the depth-temperature curves are generally too high, except for Oklahoma City and Carlsbad, where the agreement is satisfactory. At the upper levels, the values for Carlsbad and Oklahoma City are too low. The differences between the means show satisfactory agreement up to and including 60 km, but for the greater depths the values obtained from the extended depth-temperature curves are too high. Extension of the Bonanza curve leads to incorrect results as would be expected.

Assuming a reciprocal gradient of 70 feet per degree F for the synclinal areas at Bakersfield and Long Beach instead of the respective values, 53.7 and 50.4 obtained from the observations on these anticlines, the computed temperatures at depths of 30, 60, and 100 km are, respectively, 516°, 934°, and 1491° C at Bakersfield, and 495°, 913°, and 1471° C at Long Beach. These values perhaps establish a minimum for the area considered.

Suggestions

Experiments in the laboratory may show an increase of conductivity with depth that will greatly reduce the estimated temperatures from 60 to 100 km. Other corrections are to be expected at levels of discontinuity, some of which, according to Dr. Gutenberg [13], may occur between the levels of 50 and 70 km.

As a result of deep drilling and geophysical research, an accurate map showing the temperatures at the top of the crystallines is a possibility. With this map and additional data on thermal conductivities and levels of discontinuity, it will be possible to establish isogeothermal surfaces at moderate depths to a very considerable degree of accuracy. As a rule, the error of extrapolation to the base of the sediments is not very large.

Table 3--Summary of temperature-data

Item	Location and number								
	Tyrone, N.Y. (1)	Fairmont, W.Va. (2)	Oklahoma City, Okla. (3)	Carlsbad, N.Mex. (4)	Longmont, Colo. (5)	Bonanza, Ore. (6)	Bakersfield, Calif. (7)	Long Beach, Calif. (8)	Carnarvon, S. Africa (9)
Depth in feet	1750	7500	6000	6000	6500	3870	9000	9000	5003
Observed temperature in °F	81.1	170.0	127.8	111.8	210.3	200.9	241.2	245.1	157.6
Reciprocal gradients in sediments in feet per °F	50.0	50.0	69.3	99.4	41.7	25.7	53.7	50.1	44.2
Depth to basement rocks in feet	8500[a]	26000[b]	10000[c]	12000[d]	12800[e]	....	20000[f]	15000[f]	2687[g]
Estimated temperature at top of basement rocks in °F	216.1	540.0	185.5	172.2	361.4	....	446.0	364.9	....
Reciprocal gradients in basement rocks in feet per °F	93.5	93.5	129.7	185.9	77.9	25.7	100.4	93.6	82.6

[a] Interpolated from map of W. T. Thom, Jr., Ref. [5].

[b] Estimated by G. B. Richardson.

[c] Estimated by N. W. Bass.

[d] W. B. Lang, Trans. Amer. Inst. Min. Met. Eng., Petrol. Devel. Tech., p. 158, 1932.

[e] Estimated by W. S. Burbank and E. N. Goddard.

[f] Estimated by K. E. Lohman.

[g] L. Krige and H. Pirow, Trans. Geol. Soc. South Africa, v. 26, pp. 50-64, 1923.

Table 4--Estimated temperatures and differences between means

Depth		Estimated temperatures for location number as in Table 3									Calculated values by			
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	Jeffreys	Adams	Holmes	Daly
miles	km	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
6.2	10	247	323	183	140	326	719	301	291	257	350	255	343	...
12.4	20	442	518	324	238	560	...	483	486	478	580	480	600	...
18.6	30	637	713	464	336	794	...	664	680	698	680	630	800	760
24.9	40	832	908	605	434	1028	...	846	875	919	750	755	958	...
31.1	50	1027	1103	745	532	1262	...	1027	1070	1140	800	860	1088	...
37.3	60	1222	1297	886	631	1496	4266	1209	1264	1360	850	960	1206	1330
43.5	70	1416	1492	1027	729	1730	...	1391	1459	1581	910	1055	1307	...
49.7	80	1611	1687	1167	827	1964	...	1572	1654	1802	970	1140	1402	...
55.9	90	1806	1882	1308	925	2198	...	1754	1849	2023	1030	1220	1491	...
62.1	100	2001	2077	1448	1023	2432	7102	1935	2043	2243	1080	1290	1575	...

Differences between means

Depth	Mean values		Difference (a)-(b)	Depth	Mean values		Difference (a)-(b)
	1 to 5 and 7 to 9 (a)	Three computations (b)			1 to 5 and 7 to 9 (a)	Three computations (b)	
km	°C	°C	°C	km	°C	°C	°C
10	258	316	- 58	60	1171	1005	+166
20	441	553	-112	70	1353	1091	+262
30	623	703	- 80	80	1536	1171	+365
40	806	821	- 15	90	1718	1247	+471
50	988	916	+ 72	100	1900	1315	+585

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[12] R. A. Daly, reference [11], p. 233.
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THE EXTERNAL GRAVITY-FIELD AND THE INTERIOR OF THE EARTH

W. D. Lambert

It may be said at once that, in the strictest interpretation of the title, this paper does not belong in this symposium, for it is one of the fundamental theorems of gravitational attraction that the same external gravity-field may be produced by any number of different distributions of internal mass. However, the external gravity-field may be incompatible with a proposed internal distribution; furthermore, by applying our other knowledge in a common-sense way we may from a knowledge of the external field perhaps come close to the actual internal distribution of density.

A study of the external field seems to suggest that most of its peculiarities on land are due to irregularities in density fairly close to the surface. A better knowledge of gravity at sea may lead us to the same conclusion, or may modify it.

Our method of studying the internal irregularities in density by means of the external gravity-field is by the convenient mathematical fiction of surface-density. If we represent all our irregularities of internal density by means of a surface-layer of infinitesimal thickness and infinite density, we may determine the variations in the surface-layer of matter condensed upon the geoid by means of the equation [see 1 of "References" at end of paper]

$$D_R = 2[(2R/3G)\ \Delta g + N] \tag{1}$$

Here D_R is the thickness (Dicke) of the layer of ordinary rock, of density 2.76, or half the mean density of the Earth, R is the mean radius of the Earth, G is mean gravity, Δg is the local gravity-anomaly, and N is the local elevation of the geoid. N and Δg are both dependent on the formula used for theoretical gravity. The relation between N and Δg is discussed in an appendix to this paper. The accuracy of the formula is not such that it is either necessary or possible to be very precise as to just how the mean values R and G are determined. In numbers formula (1) becomes for D_R and N in meters and Δg in milligals

$$D_R = 8.65\ \Delta g + 2N \tag{2}$$

If we use the density of sea-water (1.03) instead of that of rock (2.76), we get for the equivalent depth of water (D_W) to produce the surface-layer of proper density

$$D_W = 23.2\ \Delta g + 5.36N \tag{3}$$

The name of the surface-layer may be translated from the German as "ideal perturbing layer" (ideelle störende Schicht or massenschicht), that is, the ideal layer of infinitesimal thickness that causes the gravity-anomaly Δg. The value of D_R or D_W is a way of stating the amount of matter in the layer.

To get a rough idea of the dependence of D_R or D_U on Δg, we assume on what seems to be good evidence that, within a region of moderate extent the quantity N, the elevation of the geoid above the spheroid, varies but slowly, whereas we know that Δg may vary rapidly.

The basis for Table 1 was kindly supplied me by C. H. Swick. In Table 1 the contribution to D_R given in column (5) is attributed entirely to Δg, but there is a general tendency for Δg and N to be of the same sign [2], so that the value given in column (5) is probably in most cases an underestimate. This value represents the change in the amount of rock that must be found in the immediate vicinity of each member of the pair. Since the isostatic reduction, which includes the topographic reduction, has been applied, the matter needed to explain the anomalies must be found beneath the Earth's surface. We simply cannot ram below the surface the 839 meters of rock given at the head of column (5) without doubling the density of the first 839 meters. This is not possible. We may, however, conceive that the density is increased by ten per cent over ten times 839 meters, or perhaps by 20 per cent over five times 839 meters. The gradients in column (6) must likewise be multiplied by some factor inversely proportional to the percentage-change in density. The most probable value of the factor must be decided by other evidence.

Table 1--Variations of gravity and of the ideal perturbing layer over short distances

Place (1)	Distance between stations (2)	Difference in isostatic anomaly (3)	Change of anomaly per mile (4)	Total change in D_R (5)	Rate of change of D_R per mile (6)
	miles	milligals		meters	meters
Near Cacocum, Eastern Cuba (113-114)[a]	14	97	6.93	839	59.9
Near Seattle, Washington (56-225)	21	96	4.57	830	39.5
Near Crosbyton, Texas (408-413)	23	66	2.87	571	24.8
Near Newport News, Virginia (708-709)	9	19	2.11	164	18.3
Washington, D. C. - Baltimore, Maryland (337-23)	36	45	1.25	389	10.8

[a] The numbers in parentheses are those arbitrary ones assigned to the stations in the lists published or circulated by the United States Coast and Geodetic Survey.

The passage from the ideal surface-layer of infinitesimal thickness to a layer of finite thickness gives a good approximation only when the horizontal dimensions of the region considered are large in comparison with the finite depth. This is hardly true of conditions represented by the first three lines of Table 1 but the figures are of some use in visualizing the rapidity with which irregularities in density may change.

The first three lines of Table 1 were selected for the rapidity of the change. The last two lines, Newport News and Baltimore-Washington, were selected for fairly rapid change combined with topography familiar to most of those in the audience, and tame enough topography it is on the surface. The case of Baltimore and Washington does not tell the whole story. The anomaly at Laurel, Maryland (station 209), half-way between Washington and Baltimore, is about the same as at Washington, so that the rapid change comes between Laurel and Baltimore and is about twice as rapid as the average change between Washington and Baltimore.

These rapid changes in gravity-anomaly must mean irregularities in density close to the surface. A region where the anomaly is predominately of the same sign may mean deeper-seated inequalities.

We do not have nearly as many observations of gravity at sea as we should like to have, but there seems to be a marked tendency for the gravity-anomaly in certain oceans, a tendency toward positive anomalies over large regions. Table 2 shows the mean anomaly over oceanic areas taken page by page from Vening Meinesz' report on work at sea [3].

The large positive anomaly on page 93 is especially striking. It should be said that in general the averages shown in Table 2 do not do full justice to the large positive anomalies encountered in certain regions because the means include the negative anomalies that seem to be characteristic of certain coastal regions, especially those near island arcs.

What the extended regions of positive anomaly mean I do not pretend to say, except that they must indicate an excess of matter there as compared with the land. Whether that matter is in process of adjustment by flow to other regions, that adjustment being very slow because of high viscosity, or whether the matter is maintained where it is by the strength of the Earth's crust, I do not know. Vening Meinesz [4] advocates the theory of very slow viscous flow.

Table 2--Isostatic gravity-anomalies at sea[a]

Page of report	No. of stations	Mean Hayford anomaly milligals	Mean regional anomaly milligals
89	61	+12	+11
90	62	+11	+13
91	62	+16	+15
92	61	+13	+13
93	64	+36	+36
94	59	+19	+22
95	63	+31	+20
Mean of all 432 stations		+20	+19

[a] All stations so far published by Vening Meinesz, port stations excepted.

Years ago Darwin [5] figured that the strength of the crust was about sufficient to support surface inequalities such as actually exist. More recently Jeffreys [6], making hypotheses more in accordance with actual conditions, reached about the same conclusion. Jeffreys' modifications tend on the whole to show that existing surface-inequalities are less likely to cause rupture than Darwin's calculations indicate.

If one simply notes how many times ruptures have occurred in the crust and how often it has been deformed beyond the elastic limit, it is not surprising to learn that the stresses due to existing inequalities and the stresses that would cause rupture are of the same order of magnitude.

The negative anomalies occur chiefly in narrow strips along the coast. There must be a deficiency of mass, but the geological processes that have been at work to cause this deficiency are far from clear.

We may say that the negative oceanic anomalies represent undercompensation and the positive oceanic anomalies overcompensation, but this is merely saying the same thing in a different form of words without explaining the causes, though it is a useful form when mathematical computations are to be made.

The positive anomalies might be thought of as due to the mass of a certain amount of water that has flowed in to fill the hollows created by shrinkage of the crust. Bear in mind that shallow water does not represent real deficiency of mass. Elsewhere [7] I have developed the concept of mean load level, which implies that only oceanic depths greater than about 1500 meters should be reckoned as representing deficient density. Meinesz [8] notes that positive anomalies tend to increase with increasing depth. This suggestion that certain positive oceanic gravity-anomalies represent real extra load proportioned in some degree to the depth below mean load-level is a venturesome one and, even if accepted, does not go very far. It would explain only partially the strip of negative anomalies close to the continents; partially, because a station at the edge of region of excess mass is less affected by that excess than a station in the center of it--approximately only half as much.

We must first be sure that what we are trying to explain is real and for that we need more gravity-observations at sea, especially in the open sea. There has been a tendency to concentrate attention on the very interesting strip of negative anomalies near the coast. We do not have too many observations in that negative strip--we need more--but we should not neglect the open sea. It is a matter of proportion. With a sufficient number of observations everywhere we may make notable advances toward the problem of the structure of oceanic basins.

Some mention may be made of earth-tides. The gravitational attraction of the Sun and Moon certainly affects both the vertical and horizontal components of gravity, so the study of earth-tides may be included in this paper without too great a stretch of language.

The earth-tides, like gravity-anomalies, by themselves give no absolute knowledge of the Earth's interior. A wide range of possibilities is left open but certain assumptions are excluded. A study of the earth-tides may ultimately give us the values of three pure numbers denoted in the theory of the subject by h, k, and ℓ. These numbers are defined--it is not worth while to explain the definitions--in connection with the tidal deformation expressed as a second-degree spherical harmonic and they have no meaning apart from a deformation of this type. Our ideas about the interior of the Earth should be made to fit the values of h, k, and ℓ, if we know them--a big "if".

They occur chiefly in combination as factors to reduce from an ideal unyielding Earth to the actual yielding one: (1) $(1 + k - h)$, for observations of deflections of the vertical referred to the adjacent ground; (2) $(1 + k - \ell)$, for observations of deflections of the vertical referred to the axis of the Earth, as in astronomical observations; (3) $[1 + k - (3/2)h]$, in observations of the tidal variation in the vertical component of gravity.

These factors are all expressions of the fact that the Earth yields to the tidal force. If the Earth were absolutely unyielding, h, k, and ℓ would all be zero and the factors would be unity. There has been a tendency to assume without investigation that the same factor applies in all cases and, since earth-tides were first studied by deflections of the vertical, the factor $[1 + k - (3/2)h]$ has been favored at the expense of the others.

This error of logic is the least of our troubles. The chief difficulty is the oceanic tides, which have the same periods as the earth-tides and affect them profoundly, even at great distances from the coast. We do not know what the oceanic tides amount to, except along the coast, and even if we did know, the mathematical theories to make proper allowance for the effect of the oceanic tides are inadequate or non-existent. For observations of the deflections of the vertical, historically the first, as has been noted, there is an approximate theory, but Japanese investigators, who have done much of the recent work in this field, admit that it is inadequate and unsatisfactory. For the two other methods of observation no proper method at all has been worked out, so far as I know.

With this discouraging preamble, you will not expect any very definite set of conclusions. It does emerge, however, that the Earth, on the average, is about twice as rigid as steel and that this rigidity may reside chiefly in the layers down to about 3000-km depth, and that the central core of the Earth may be liquid, as many seismologists would have it, as far as earth-tides are concerned [9]. "On the average" is, of course, a conveniently vague phrase but is susceptible of a more definite meaning if we admit a very conventionalized model of the Earth that is rather far from reality.

This is not the place for a bibliography of earth-tides. References to the works of Love, Larmor, Schweydar, Jeffreys, various Japanese investigators, and others who have worked on the theory and observation of earth-tides can be found [9]. Besides improvements in the theory of earth-tides and in the knowledge of oceanic tides, we need further direct observation. It would be desirable to get the two horizontal components of the tidal effect and the vertical component all at the same place, and to do this for a large number of places.

A moot question is the effect of surface-features, such as faults or other discontinuities, on earth-tides. My personal opinion is that such an effect is probably small, but others hold a contrary view. It would be interesting to establish two sets of instruments so near one another that the direct tidal forces and the indirect forces arising from the oceanic tides would be practically identical, but to put one set on one side of a discontinuity and the other set on the other. In this way the effect of the discontinuity, if perceptible, would be brought out. Conceivably there might be a perceptible difference between regions where deep-focus earthquakes are prevalent and regions where they are not.

Astronomical observations give us some evidence about the external gravity-field of the Earth. The ellipticity of the Earth affects the motions of the Moon's perigee and node, and the Moon and Sun acting on the equatorial bulge of the Earth produce nearly all of the observed precession of the equinoxes. If our observations were accurate enough, we might by a comparison of these two effects decide whether the internal strata of the Earth had ellipticities corresponding to internal fluidity or not, but the observations are not accurate enough.

The motions of the perigee and node can be observed rather accurately and are in very large part due to the action of the Sun; this part can be calculated with considerable accuracy by the aid of the highly intricate mathematical theory of the Moon's motions. The small residual effects are due to the flattening of the Earth. Observation and lunar theory are sufficiently accurate to enable us to deduce from these small residuals a value of the flattening having a probable error of about the same magnitude as the error from geodetic determinations.

On the other hand, the precession of the equinoxes can be observed with great accuracy and from this we can set limits to the flattening and actually assign to it a value, if we make assumptions about the internal condition of the Earth. If we do assume internal fluidity, it matters surprisingly little what law we assume for the variation in density between center and surface, provided other known conditions are satisfied. The flattening obtained on the assumption of internal fluidity is very nearly the same as that determined by the motions of the perigee and node and by geodetic evidence, all of which are independent of any such assumption, but the probable errors are not such that we are justified in asserting that there either is or is not any marked departure from internal fluidity. The figure of the Moon complicates the discussion of the motions of the perigee and node, and evidence on the figure of the Moon is conflicting [10].

Summary

To summarize briefly: Observations of external gravity give us no absolute determination about the distribution of densities within the Earth but they tell us what can not be and, carefully considered, they may afford valuable hints as to what actually is.

If we adopt the mathematical fiction of a surface-layer, an adequate net of gravity-anomalies distributed over the Earth would enable us to determine both the density of this ideal surface-layer and the deviations of the geoid from the spheriod of reference, since the density of the layer and the difference between the geoid and spheriod may be considered as cause and effect and the gravity-anomalies as the resultant of both.

On land the rapid variation in the gravity-anomaly that sometimes occurs between one locality and another nearby indicates irregularities close to the surface. At sea there appear to be extensive areas of positive anomaly. These may represent deeper-seated anomalies in density, but excess of mass they must be. More detailed observation may show us whether conditions of rapid variation between one point and another prevail at sea, as on land.

These positive anomalies at sea may conceivably be due to the condensation of the crust to form hollows into which the sea has flowed to form an excess load. The strength of the materials composing the crust seems just about sufficient to support existing inequalities of the surface, but the excesses or deficits of matter represented by positive or negative anomalies may not represent a permanent condition of affairs. The subcrustal condition may be subject to a very slow viscous movement of equalization, as Vening Meinesz, Pekeris, and others believe. The negative anomalies found so often along shore, especially near island-arcs, certainly represent deficiencies of density but their meaning is an outstanding geological puzzle.

Earth-tides again can tell us what conditions can not exist but do not tell us what conditions actually prevail. There are many difficulties, both observational and theoretical, connected with the problem of the earth-tides and many more observations are needed.

Observed values of earth-tides, such as they are, are not incompatible with the hypothesis of a fluid core surrounded by an outer shell of high rigidity, the average modulus of rigidity being about twice that of steel.

There are two methods of determining the flattening of the Earth by astronomical methods: One by means of observed motions of the perigee and node of the Moon in connection with some rather intricate lunar theory; the other by means of the precession of the equinoxes. The first method is independent of the internal condition of the Earth and the results derived from it agree within reasonable limits of errors with the results found by geodetic means and from the precession, the latter method involving the hypothesis of internal fluidity. The gravity-field determined astronomically is again of little use in judging of conditions in the interior of the Earth, except that we may say that they do not contradict the hypothesis of fluidity under the action of long-time stresses.

The relation between the gravity-anomaly and the ideal surface-layer is further discussed in an appendix. A second appendix discusses some of the mathematical conditions to which the ideal surface-layer is subject.

Appendix I--Determination of the "ideal perturbing layer" from the gravity-anomalies

If we have a sufficiently dense net of gravity-anomalies all over the Earth, then by Stokes' formula we can determine N, the elevation of the geoid at any point, and then the thickness of the excess or deficiency of matter (ideal perturbing layer, ideelle störende Schicht) by means of formula (1). Stokes' formula, however, seems a piece of mathematical jugglery and the terms of the formula have no direct physical meaning. Equation (1) can be used to find N and D_R by a process of successive approximations that appeals more to the intuitions than Stokes' formula does. The process is also of some service even when our net of values of Δg does not cover the entire globe.

The price that one pays for the more immediate appeal to intuition or for the absence of complete data is an increase in labor.

Take equation (1), or (2) modified to fit any assumed density, and first neglect N, attributing D_R to Δg alone. Do this for all available gravity-stations. Estimate D_R for the regions between gravity-stations. This value of D_R gives rise to a potential and a consequent warping of the geoid. Compute this warping from Table 1 of Special Publication No. 199 of the United States Coast and Geodetic Survey, "Tables for determining the form of the geoid and its indirect effect on gravity." The quantity there called H is the N of (1) or (2), apart from a density-factor. The argument h of the tables is the D_R just found. As the perturbing layer is of infinitesimal thickness, though we visualize the amount of matter that it contains as of finite thickness, it is fairest to take a mean value of H (or of N) for the values of h (or of D_R) for numerically equal positive and negative values of h. Since H is for unit-density, the result found must be multiplied by the assumed density. The product is a first approximation to N. Call it N_1. If we are using (2), use the value of N_1 for N to get an improved value of D_R. Make another estimate of D_R and repeat the process to get a better--and generally a larger--value of N, which call N_2. Use this N_2 as the N of (1) or (2) and get a still better value of D_R.

The process should theoretically be continued indefinitely, but practically it should converge with fair rapidity, so that a few repetitions should suffice.

The process outlined above is essentially that given by Poincaré in his article "Les mesures de gravité et la géodésie" (Bull. Astronom., v. 18, pp. 23-26, 1901). Poincaré states that in his form of the process the convergence is like that of geometrical progression with ratio 3/5 but indicates methods of making the convergence more rapid.

Appendix II--Mathematical conditions to which the ideal perturbing layer is subject.

The ideal perturbing layer (ideelle störende Schicht) is subject to certain mathematical conditions expressible by the vanishing of certain spherical harmonics of degrees zero, one, and two. The conditions are in part implied in Stokes' classical memoir [11], especially as regards harmonics of degrees zero and one, and would properly be mentioned in all other thorough treatments of Stokes' method for inferring the form of the geoid from the gravity-anomalies. Those of the second degree are mentioned in the author's [12] paper and again in a note by Jeffreys [13].

If the ideal perturbing layer D_R be expanded in a series of surface spherical harmonics

$$D_R = u_0 + u_1 + u_2 + u_3 \cdots \qquad (A)$$

where the u's are spherical harmonics of degree indicated by the subscript, then u_0 must be zero; otherwise we would be adding to or subtracting from the mass of the Earth. An expansion of Δg in spherical harmonics should likewise have its harmonic of order zero vanish, but if we start with a development of Δg having by mistake a non-vanishing term of order zero, the values of N deduced by Stokes' method are not affected, but the values of D_R are, as is seen from equation (1) of the main paper.

The terms of the first degree, represented by u_1 in (A), have to do with the position of the center of gravity and the term in u_1 may be made to vanish by a suitable choice of the origin of coordinates, making the origin coincide with the center of mass of the whole system, including the perturbing layer. The presence of a term of the first degree in the spherical-harmonic expansion of Δg means that an impossible set of gravity-anomalies has been assumed, but such a term does not affect the value of N, but it does affect D_R, as is again seen by reference to (1).

If we look at a map of the world or at a globe, there is an obvious lack of symmetry in the distribution of land and water; first, as between the Northern Hemisphere, which is predominantly land, whereas the Southern Hemisphere is predominantly water, and second, as between the Eastern Hemisphere, with the great land-masses of Eurasia and Africa, and the Western Hemisphere, with the relatively smaller land-masses of the Americas. If we take land and water at their face value, the one representing an excess of mass and the other a deficiency of matter, there is an evident lopsidedness in the distribution of mass. The apparent center of mass of the whole Earth lies 804 meters to the north of the equator and projects outward 834 meters in longitude 31° east [14]. Isostatic compensation, defined as equality of the mass of the compensation with the mass of the topographic feature or features compensated, reduces the figures for the lopsidedness to a small fraction of the amounts given but does not abolish it. There must be something else besides isostatic compensation as ordinarily computed in order to make the corresponding terms in D_R vanish. The presence of terms of the first degree in the expansion of Δg corresponding to terms of this type does not affect N, as already noted, but does affect D_R. Perhaps there is room for a certain amount of overcompensation in certain areas of the Pacific and the Atlantic in order to offset the displacement of mass to the north of the equator and to the east of Greenwich.

As regards the compensation of the Pacific Ocean as a whole, Jeffreys' words on page 6 of his pamphlet on "The problem of oceanic structure" are worth quoting:

> "We can say that the general uniformity of mass per unit area holds as between the Pacific Ocean and the rest of the Earth, taken as wholes. This depends on a fundamental theorem in the theory of attractions. To take an elementary case, suppose we have a uniform sphere covered with water; in equilibrium the water will cover the whole to a uniform depth. Now suppose we try to make a land hemisphere by shaving off the surface on one side and spreading it over the other. The process shifts the center of mass, the water redistributes itself about the new center of mass, and in spite of our efforts the sphere is still covered to a uniform depth. This is only a special case of a much more general result, involved in MacCullagh's theorem and in Stokes' theory of the figure of the Earth: gravity over a level surface cannot contain any first harmonic term, and the centroid of a level surface is the center of mass of the Earth. This involves no assumptions about the Earth's structure and is a direct consequence of the law of gravitation. A first harmonic necessarily has opposite signs over opposite hemispheres, and the Pacific covers practically half the Earth's surface. Two consequences follow at once. The mean value of gravity over it, at sea-level, cannot differ from the mean value over the other half, reduced to sea-level according to the free-air formula. Also the centroid of the level surfaces is the center of mass. But the solid surface is not a level surface, but projects systematically on one side and is depressed on the other. The center of mass can therefore be at the centroid of the level surfaces only if the projecting side has a lower density than the depressed one. Thus the general compensation of the Pacific can be inferred from the mere fact that it is an ocean, and observations of gravity over it do nothing to confirm or deny the compensation."

The terms of the second degree in the expansion of D_R have to do with the pole of figure (really a pole of mass or inertia, the pole of the axis of maximum moment of inertia) and the pole of rotation. These two poles actually coincide with a fraction of a second of arc, but if we take land and water at their face values as excesses or deficits, they would fail to coincide by more than a degree. Isostatic compensation in the ordinary sense reduces the distance between them to something of the order of a minute of arc [15]. Again something slightly different from ordinary compensation applied in a uniform way all over the Earth is needed to bring the two poles into coincidence.

The definition of complete isostasy as equality of the mass of the compensation with the mass of the feature compensated is only one of many possible definitions. Various definitions have been suggested that would make the equality only approximate. A very limited amount of experience on land suggests that the mass of the compensation may be slightly less than that of the topography. (Not enough has been published to yield satisfactory references. The Survey of India has found that in general the "isostatic geoid" is smoother than the actual geoid. The inequalities in the isostatic geoid could be made more marked by diminishing slightly the mass of the compensation. The same tendency was found in the United States but the results have not been published because pressure of routine work prevented the completion of the investigation and, in any case, the deflection stations were too far apart to afford any certainty that a close approximation to the actual geoid could be attained. The matter was discussed in the meetings of the Committee on the Geoid during the sessions of the Association of Geodesy at Edinburgh in 1936. It is expected that these discussions will be published in the Bulletin Géodésique.) On the other hand, overcompensation seems to be indicated for certain areas at sea and, if judiciously applied, would take care of the difference between the actual and the apparent center of mass.

If we use mean load-level, already referred to, as the level from which to reckon our topography, systematic overcompensation or undercompensation stated in terms of mass over the whole Earth will take care of itself as far as the harmonic of degree zero is concerned. But if we wish to take care of the other conditions to which our ideal perturbing layer is subject, and especially if we apply different hypotheses in different parts of the Earth, we must examine each case by itself to see that the necessary conditions are satisfied. To repeat, they are that in the expansion of D_R in spherical harmonics:

Degree zero $u_0 - P_0 = 0$

Degree unity $u_1' = 0$

which requires that its separate parts be zero, that is,

$$A_1P_1 = 0 \qquad B_1P_1{}^1 = 0 \qquad C_1P_1{}^1 = 0$$

These are all the harmonic terms of degree unity.

Degree two $\qquad A_2P_2{}^1 = 0 \qquad B_2P_2{}^1 = 0$

These equations imply coincidence of the poles of mass and of figure.

The other terms of degree two need not be zero. The term in $P_2{}^0$ implies a change in flattening. The term in $P_2{}^2$ gives a longitude-term.

In the above terms $P_n(\sin\varphi)$, where φ is the latitude and P's are the usual zonal harmonics. P_0 = constant, $P_1(\sin\varphi) = \sin\varphi$, $P_2(\sin\varphi) = [(3/2)\sin^2\varphi - 1/2]$, etc. The associated harmonics are given by $P_n{}^k(\sin\varphi) = \cos^k\varphi \dfrac{d^k}{d(\sin\varphi)^k} P_n(\sin\varphi)$.

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DEEP-FOCUS EARTHQUAKES AND THEIR IMPLICATIONS

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No one any longer doubts that earthquakes occur at depths of several hundred kilometers. There is not the same unanimity in regard to the absolute depth of focus of these earthquakes, the relative merits of methods for measuring the depth, the character, and distribution of plutonic earthquakes; and especially is there disagreement as to their causes and mechanism and as to their geological implications.

Several methods have been suggested for the measurement of depth of focus. Most of these are relative methods. Turner based his estimate of the relative depth of focus on the degree of earliness in the arrival time of longitudinal waves at the antipodes in the case of deep shocks as compared with normal earthquakes. Stechschulte took as his criterion the interval between the arrival of the direct longitudinal wave and that of the Walker reflection at the distance at which this interval reached its maximum. Scrase used Knott's calculations to determine the depth of focus from the departure of the travel-time curves for deep earthquakes from those of normal earthquakes. Wadati has suggested a number of methods: First, the spacing of the isochrones or lines of simultaneous arrival; second, the time-intercept of the graph of the interval between the arrival of the longitudinal and that of the transverse waves against the absolute arrival time of the longitudinal waves; third, he used tables of calculated travel-times from deep foci based on those of shallow earthquakes, each set of tables corresponding to a given depth of focus. Miyamoto determined the depth of focus by comparing the travel-times of longitudinal and transverse waves reflected from the core of the Earth with those for normal earthquakes. Berlage uses the interval between the arrival of the direct longitudinal wave and that of the Walker reflection for direct calculation of the depth. Sohon used a chart of curves based on Wadati's tables. Gutenberg and Richter have calculated tables of corrections for depth of focus to be applied to their tables for normal earthquakes. These corrections are based on the observed travel-times of such phases as the longitudinal waves which traverse the core, are reflected on the far side of the Earth and return through the core to the station as well as on Gutenberg's calculations of the velocity-depth relation. Ultimately all of the methods depend on four factors: First, the depth of focus which corresponds to the normal tables or curves used; second, the departure of the travel-times of deep earthquakes from normal; third, the observed intervals between phases and especially between the direct phases and the Walker reflections; and last, the velocity-depth relation in the Earth. Most of the normal tables in use are based on averages for many earthquakes which are probably heterogeneous both as regards crustal structure in the neighborhood of the focus and as regards focal depth. This heterogeneity is carried over into the curves for deep earthquakes. However, such systematic errors do not seem to be large. Bois has made a comparison of several of these methods and finds that they agree within ten per cent. It may be noted in passing that Bois completely misunderstands the origin of the Brunner curves. These curves were originally constructed on a purely observational basis without reference to any hypothesis as to velocity-distribution in the Earth. The normal curves to which they were referred were the Macelwane curves of 1933. Recently Dahm and Blum calculated the velocity-depth relation which follows from the form of the Brunner curves and they found that it coincides almost exactly with the velocity-depth distribution for the Tango earthquake region determined by the Wiechert-Herglotz solutions of Dahm.

The variation of a few per cent between results obtained by the different modern methods for calculating depths of focus may be traced in part to the four factors mentioned above and in part to differences in the selection of observational data on which the curves are based. But there seems to be a more fundamental reason for this slight disagreement. Recent work seems to suggest that structural differences extend to great depths so that the same reduction cannot be applied to every deep earthquake since the velocity-depth relation in the epicentral region of one may not be the same as that in the epicentral region of another. We are greatly in need of more studies of individual earthquakes and of more solutions for individual regions. Nevertheless, it may be considered a great triumph of modern seismology that we are able to determine absolute depths within such narrow limits.

Earthquakes with depths of focus of hundreds of kilometers to which the name plutonic has been given may be very violent and a large part of the elastic energy thus released is in the form of shear-energy. Sometimes the shear-energy greatly predominates. These earthquakes are numerous. They are widely distributed, but it will require a much longer period of study before it will be possible to determine with any degree of probability their relation to normal earthquakes. While the long series of after-shocks usually attendant upon strong earthquakes of normal depth do not seem to characterize plutonic earthquakes, nevertheless after-shocks are not excluded.

Among the hypotheses that have been suggested to account for the occurrence of plutonic earthquakes, one is based in part on the explosive changes under great hydrostatic and shearing forces which were observed by Bridgman and may be stated briefly as follows: Progressive modification of the dynamic and thermodynamic conditions underneath the crust of the Earth may result in a state of unstable equilibrium requiring only a trigger force to produce an explosive change of state. This hypothesis would seem to be excluded by the seismological evidence since it is difficult to see how an explosive phenomena could possibly give rise to shear-waves of so much energy as those which are frequently observed in the records of plutonic earthquakes. The second hypothesis is that stated by De Lury (J. Geol., v. 43, pp. 759-764, 1935):

> "A rational hypothesis for the mechanism of earthquakes of deep origin seems to be permitted by the evidence: If an initial thermal gradient has been disturbed to depths greater than 700 km, rocks above those depths should in general have temperatures sufficiently remote from fusion conditions for the confining pressure to give them great strength. It might be asked, however, if this general condition excludes the possibility of a continuous shell of weakness in shallower levels. In answer it can be said that geothermal evidence is opposed to the existence of a shell of weakness and favors the view that the outer Earth is being continually distorted by thermal activities. The evidence that earthquake foci are found at many levels down to depths of 700 km, gives definite confirmation of this view. Expansion and contraction, brought about by differential generation and conduction of heat, in rocks of great strength, seem to be the most promising source for the great stresses required by deep-seated earthquakes."

It is clear that this hypothesis would account for the great energy of many deep earthquakes by allowing for the gradual storage of elastic strain in rocks of sufficient strength at depths of hundreds of kilometers and its sudden release when the stress becomes greater than the strength of the rocks. A third hypothesis that has been suggested supposes the rocks at the depths of plutonic foci to be crystalline in character, or at least assumes the possibility of crystallization. The changes of temperature and pressure which are brought about by change of depth through erosion and deposition on the surface of the Earth and by radioactivity within will have a greater tendency to uniformity parallel to the surface than perpendicular to it. Hence crystallization or recrystallization into minerals of different density and volume may be supposed to progress asymmetrically as a horizontal lens or wedge rather than as a spherical body. This asymmetry will introduce into the surrounding medium an increasing state of strain, a large part of which will consist in change of form. Assuming that the surrounding medium has sufficient strength to store the strain-energy, or at least that the viscosity is sufficiently high and the process sufficiently rapid to allow temporary storage, there will come a time when the surrounding medium will be strained beyond its ultimate limit so that fracture and readjustment will occur. A fourth hypothesis is that proposed by Gutenberg and Richter (Bull. Seis. Soc. Amer., v. 28, pp. 341-390, 1936):

> "The problem of the causative mechanism of these shocks has not yet been solved completely. The complex patterns of initial observed compressions and dilations, and the frequent observation of large shear-waves (S), make explanations in terms of an explosive or collapse type of origin improbable; apparently the originating movement is accompanied by shear. The geographical distribution of shocks recorded with initial compression or dilatation at Pasadena indicates that in general this shearing or faulting movement has the same direction over large areas, persists over long periods of time, and is frequently the same for all focal depths in the given region (including normal shocks).
>
> "The fact that large stresses can accumulate at great depths does not necessarily imply great strength at these depths; for, as has been shown by Haskell, the high coefficient of viscosity prevents rapid flow even if there is no strength. As is shown by the recurrence of shocks from the same focus, only a few years may be required for the accumulation of stresses sufficient to produce a large earthquake. On the other hand, during such a time-interval, theoretically only a small fraction of the stress should be removed by plastic flow. The calculations of Haskell show further that the stresses at the surface are accompanied by only slightly smaller stresses at depths of a few hundred kilometers, and vice versa. This would explain the occurrence of shallow and deep earthquakes in the same regions. The results found by Stetson on the periodic relation of deep-focus earthquakes to the tidal forces might also be explained in this way.
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> "The most probable conclusion, in the present state of our knowledge, is that normal and deep-focus earthquakes are brought about by the same forces, which may act either near the surface or at great depths."

Gutenberg bases his hypothesis first on the calculations of Haskell, which indicate that the deformation produced by a force applied at the surface of the Earth dies out rather slowly with depth; second, on the theory of Daly that the subcrustal materials have no strength in the sense defined by Jeffreys; third, on the assumption that these materials have such high viscosity that they are able to store enormous quantities of strain-energy long enough to be released by elastic rebound along a fault-plane in a manner similar to shallow faulting. One objection to this hypothesis is the difficulty of seeing why the final yielding and consequent faulting should begin at great depth where the stresses are less rather than near the surface where they are greater.

In conclusion, let me say that the two facts which seem to emerge as indisputable are that earthquakes do occur at depths of hundreds of kilometers and that their character requires at least temporary storage of immense quantities of energy of elastic strain including shear.

The problems that remain unsolved include: First, the geographical distribution of plutonic earthquakes and their possible relationship to deep-seated major structures; second, their vertical distribution and their possible concentration at certain depths; third, the mechanism of plutonic earthquakes and its relation to the thermodynamic conditions and the physical and chemical characteristics of the subcrustal materials in which they occur; fourth, the ultimate causes of these earthquakes. In connection with these problems one cannot stress too strongly the necessity of keeping an open mind with regard to alternative or multiple hypotheses until any or all of them will have been excluded by incontrovertible evidence.

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THE EARTH'S INTERIOR AS INFERRED FROM TERRESTRIAL MAGNETISM

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Those who have attempted to picture the Earth's interior seem to have paid little or no attention to the inferences which may be drawn from terrestrial-magnetic phenomena. Yet, no conception of the physical state of the Earth's interior can be complete and correct which fails to account for the facts of its magnetic condition. Furthermore, the study of terrestrial magnetism supplies information regarding the Earth's interior which is not revealed by any of the other geophysical sciences.

The Earth's substance produces a magnetic field in space. Large changes in this magnetic field occur within exceedingly short intervals of time, which are due to changes occurring within the Earth. Study of more rapid changes indicates that the electric conductivity of the material increases some two orders of magnitude at a depth of about 200 km--a region where other lines of evidence fail to reveal discontinuities. Attempts to account for these facts in accord with the usual concepts of the Earth's interior have been notably unsuccessful.

The existence of a magnetic potential for the Earth is as definite a fact as the existence of a gravitational potential. Mathematical analysis [see 1 of "References" at end of paper] has shown that the major portion, over 90 per cent, of this magnetic potential originates within the Earth and may be closely approximated by the three harmonics of first degree. The importance of the first-degree harmonics is illustrated in Figure 1, where they appear at the top of the Figure, drawn to one-tenth the scale used for the higher-degree harmonics. The two harmonics $\sin\theta\cos\lambda$ and $\sin\theta\sin\lambda$ have been combined into $\sin\theta\cos(\lambda+\lambda_0)$. Physically, these three first-degree harmonics are equivalent to a uniform magnetization of the entire substance of the Earth parallel to a diameter, called the axis of uniform magnetization, intercepting the surface in a point about 78°5 north and 69° west, as determined from Bauer's analysis. The magnetic moment represented by these harmonics is 8.04×10^{25} cgs units, or 0.074 cgs unit per cubic centimeter for the entire volume of the Earth. Such magnetization would result if an ordinary embroidery-needle, highly magnetized, were imbedded in every five cubic centimeters of the Earth's substance. The explanation of this magnetization constitutes the greatest problem of terrestrial magnetism.

According to present knowledge, magnetic fields may result from only two causes--permanent magnetization or electric currents. The latter cause includes motion of electrostatic charges. Magnetization by rotation may be regarded as an aspect of permanent magnetization. Unless some unknown principle of physics is invoked, the magnetic field of the Earth must be explained by either of these causes acting below the surface.

Several attempts have been made to explain the Earth's field by appropriately disposed electric charges which partake of its rotation [2]. These theories have all encountered insuperable difficulties. Furthermore, such theories can explain only that portion of the Earth's uniform field which is symmetrical with respect to the axis of rotation--the component of the uniform field which is perpendicular to the axis of rotation and is one-fifth as great as the rotationally symmetric part remaining unexplained. The criticism applies equally well to the theory of magnetization by rotation, which fails to account for even the symmetric field by several orders of magnitude, and to any other theory which associates the magnetization of the Earth with its rotation.

Lamb [3] has shown that a current once set up in a sphere of copper the size of the Earth would die down very slowly, sinking to 1/e of its original value in 10,000,000 years. Even if the Earth had an electric conductivity as great as copper, the intensity of its magnetic field in accord with such a hypothesis would have been enormous in past geologic eras. Other evidence indicates that the electric conductivity at depths as great as one-tenth of a radius is very much less than that of copper and that currents flowing at those depths die out in a few days. The hypothesis that the Earth's field is due to electric currents circulating in the interior appears to require a mechanism for sustaining those currents. One such mechanism has been proposed by Larmor [4] who suggested that the circulation of semi-fluid matter within the Earth produced electric currents by cutting the lines of magnetic force. Cowling [5] has taken exception to this assumption and argued that the magnetic effects cannot be self-sustaining as hypothesized by Larmor. Gunn [6] has proposed a Nernst-Ettinghausen effect to sustain the currents, the electromotive forces arising from the crossed thermal gradient and magnetic field. It seems that Cowling's objection must also be raised against Gunn's hypothesis and against any other hypothesis which requires that the magnetic field and the currents which produce it are mutually self-sustaining.

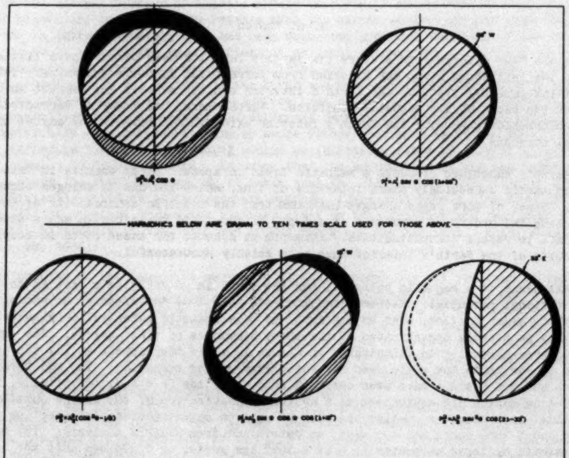
HARMONICS BELOW ARE DRAWN TO TEN TIMES SCALE USED FOR THOSE ABOVE

FIG. 1—REPRESENTATION FIRST 13 HARMONIC COMPONENTS OF EARTH'S MAGNETIC FIELD

In the absence of any other satisfactory explanation, the belief that the Earth is ferromagnetic suggests itself. However, the thermal condition of the Earth as usually deduced from observed surface-gradients and other considerations suggests that matter at depths below about 20 km is above the Curie-point. According to this view only a thin crust is capable of permanent magnetization. That so thin a crust should give rise to the entire magnetic field would require that every five cubic centimeters contain not one but 100 of our hypothetical magnetized embroidery-needles. All of these magnetic elements would have to be aligned parallel with the magnetic axis--at the poles they would be perpendicular to the Earth's surface and at the equator, parallel to it. Thus at the poles the thickness of the magnetic material, measured along the direction of magnetization, would be 20 km while at the equator the direction of magnetization would extend 7000 km in places without interruption. For this reason the demagnetizing force would be much greater in polar regions than in equatorial regions and would, therefore, cause the polar regions to be less strongly magnetized. Differences in the geothermal gradient under oceans and under continents, such as undoubtedly exist, would also give rise to great inhomogeneities in the magnetic field. The dominance of the first-degree terms in the potential-analysis of the magnetic field argues against a crustal origin; in particular, no term appears in the potential series which corresponds to the greater intensity of magnetization to be expected in equatorial regions. The required magnetization of this thin crust and the composition of that portion of the crust which is exposed and can be examined in a laboratory are difficult to reconcile.

The possibility that great pressures may raise the Curie-point sufficiently to permit ferromagnetism at temperatures which are believed to obtain within the Earth has been considered. Experimental investigations of this possibility have yielded negative results. Adams and Green [7] observed the Curie-point for several ferromagnetic substances at pressures up to 3500 atmospheres (corresponding to a depth of about 14 km) and detected no change within the limits of accuracy of their measurements. To permit ferromagnetism at the temperatures which are assigned to the Earth's interior the Curie-point temperature would have to increase about 0°.01 for a pressure-increase of one atmosphere. So large a change as this, if it exists, would be revealed by the experiments. The possibility that the Curie-point temperature may increase sharply at very great pressures is not precluded by the experiments.

The fact that the Earth's internal substance does produce a magnetic field in the space about it, in view of the foregoing considerations, calls into question the validity of the temperatures assigned to it. Temperatures assigned to the Earth's interior are based upon a number of assumptions: (1) That the Earth was originally molten; (2) that it cooled rapidly by convection until the thermal gradient equalled the variation of melting-point of rocks with pressure, taken as from 3° to 5° per km of depth; (3) that thereafter cooling has been by conduction for about 10^9 years; (4) that the thermometric conductivity is the same at all depths and is equal to that observed for surface-rocks. If the relation between melting-point and temperature does not hold at great depths, or if the thermometric conductivity is markedly different, the actual thermal state of the Earth may differ considerably from the inferred one. Data from terrestrial magnetism, which will be discussed later, supply reasons for supposing that the thermometric conductivity at great depths differs considerably from that observed for surface-rocks. The

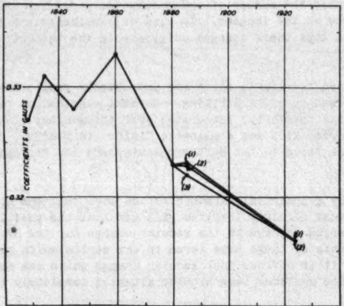

FIG. 2A—COEFFICIENTS OF HARMONIC WHICH REPRESENTS UNIFORM MAGNETIZATION FROM DIFFERENT ANALYSES

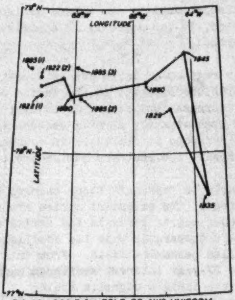

FIG. 2B—POSITION POLE OF AXIS UNIFORM MAGNETIZATION FROM DIFFERENT ANALYSES

[SOURCES: 1829, ERMAN AND PETERSEN; 1835, GAUSS; 1845, ADAMS; 1860, CARLHEIM-GYLLENSKÖLD; 1880, ADAMS; 1885, SCHMIDT (1), FRITSCHE (2), NEUMAYER AND PETERSEN (3); 1922, FURNER AND DYSON (1), BAUER (2)] single fact that the Earth possesses a magnetic field constitutes one good reason for supposing that a considerable portion of its matter is below the Curie-point temperature.

Changes in the so-called permanent magnetic field of the Earth reveal large-scale variations in some property of the Earth's interior. How much of the magnetic secular change may be attributed to changes in the uniform magnetization of the Earth is a moot question. Figure 2A shows the change in the coefficient of uniform magnetization (into which all three of the first-degree harmonics have been combined) as revealed by various analyses spread over a century. Little significance can be attached to values from the earlier analyses since many parts of the Earth had been unexplored, magnetically, at those times. The change from 1885 to 1922 is determined by fairly good data and indicates a decrease in uniform magnetization of about two per cent in 37 years. Much of the change may be attributed to the use of more complete and accurate data in the later analysis. Apparent changes in the direction of uniform magnetization are revealed by Figure 2B, representing the position of the pole of the axis of uniform magnetization determined by the various analyses. An apparent westward movement of the axis-pole is suggested, but since the shift from 1885 to 1922 is slight, the apparent effect may be due to incompleteness or inaccuracy of the data. The view that the magnetic axis-pole is moving westward at _ rate so that it will circle the geographic pole in a few centuries is not strongly supported by Figure 2B.

On the other hand, unambiguous evidence that large changes have occurred in the magnetic field over considerable portions of the Earth is presented in Figures 3 and 4. These charts were constructed from the differences in values of the magnetic elements used by Schmidt [8] in his analysis for the epoch 1885 and by Furner and Dyson [9] in their analysis for the epoch 1922. For sparsely settled and inaccessible portions of the Earth the charts may be quite inaccurate but elsewhere they are probably quite accurate. It is to be noted that the largest changes are not entirely assigned to unexplored regions--those places where the ancient cartographers drew monsters and mermaids--but actually occur where no stretch of imagination can attribute them to faults of observation.

The large center of secular change in vertical intensity off the Guinea Coast in Figure 4--amounting to a decrease of 0.06 gauss in the flux-density passing into the Earth--is unquestionably real. Its origin is beneath the Earth's surface because the vectors representing change in the horizontal components of the flux, shown in Figure 3, point away from the region. If its origin were above the Earth's surface, the horizontal-intensity vectors would point toward the center. The accuracy of the charts in this region is attested by the horizontal-intensity vectors being everywhere approximately perpendicular to the isopors of vertical intensity. This change of 0.06 gauss in vertical intensity during the 37-year interval from 1885 to 1922 is nearly one-tenth as great as the maximum field at the Earth's surface due to uniform magnetization.

An approximation following a method due to Chapman [10] indicates that this change would require the addition of 5×10^{15} of our hypothetical embroidery-needles beneath each square kilometer of the Earth's surface at the center of change, their north-seeking poles pointing downward, or the removal of an equal number, the north-seeking ends of which had been pointing upward. At various distances from the center the number of these embroidery-needles required is roughly proportional to the values assigned to the isopors. In view of considerations previously mentioned, it can scarcely be conceived that these changes originate in the thin outer crust of the Earth.

Other regions of large change appear on the charts which are undoubtedly real. The secular change which has occurred in the Indian Ocean is quite striking. Careful examination reveals that the increases and decreases in vertical intensity, integrated over the surface of the Earth, add up to approximately zero--a necessary condition for a magnetic field. In general, the changes correspond to decreases in downward force in the Northern Hemisphere and decreases in upward force in the Southern Hemisphere.

Attempts to represent these changes by a spherical harmonic series show that the higher-degree terms of the potential series are most strongly involved [11] and that the coefficients of the higher-degree terms in the series which represents the secular change for the 37-year interval are comparable with the coefficients of those same terms in the series which represents the so-called permanent field. From this it is obvious that secular change which has occurred during the 37-year interval mentioned cannot continue long without altering completely the entire aspect of the Earth's magnetic field.

If that portion of the Earth's magnetic field which may be ascribed to uniform magnetization

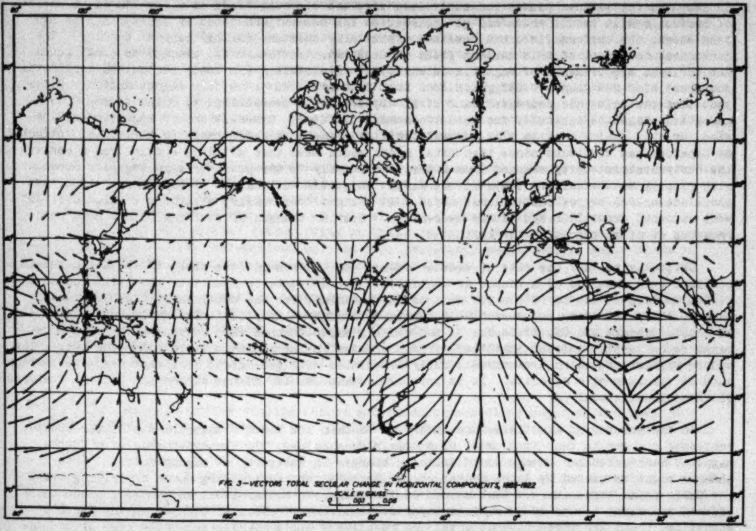
SCALE IN GAUSS
0 0.03 0.06
180°
120°
60°
0°

FIG. 3—VECTORS TOTAL SECULAR CHANGE IN HORIZONTAL COMPONENTS, 1885-1922

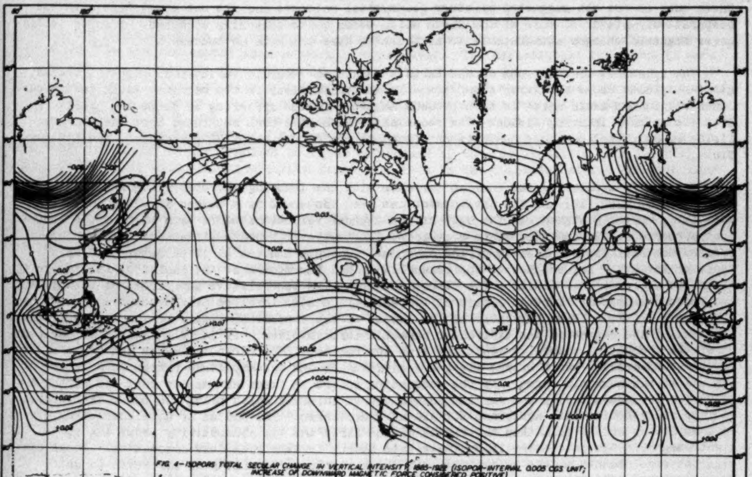

FIG. 4—ISOPORS TOTAL SECULAR CHANGE IN VERTICAL INTENSITY, 1885-1922 (ISOPOR-INTERVAL 0.005 CGS UNIT; INCREASE OF DOWNWARD MAGNETIC FORCE CONSIDERED POSITIVE)

is computed for various places and subtracted from the observed field at those places, a series of residuals will result which may be regarded as the non-uniform field of the Earth. As has been shown, the uniform field has remained essentially constant during the past century. The horizontal component of this uniform field at Capetown, South Africa, amounts to 0.245 gauss. The earliest measurements of magnetic intensity at this station (in 1843) indicate a horizontal component of 0.209 gauss, 0.036 gauss less than intensity due to uniform magnetization. Since that time the value has decreased (and still appears to be decreasing) to 0.150 gauss--0.095 gauss less than the intensity due to uniform magnetization. Observations of magnetic inclination, or dip, dating back to 1751 suggest that the present rate of change in horizontal intensity at Capetown has continued since that date, which would mean that within a little over a century the horizontal intensity changed from a positive anomaly to the present large negative anomaly with respect to the uniform field of the Earth. Magnetic declination at Capetown in 1605 was about one-half a degree east of true north. It changed continually, attaining a value over 30° west of north about 1865 and is now decreasing. Similar changes of striking nature have been recorded at other places on the Earth.

Obviously neither the rate of secular change nor the non-uniform field of the Earth remain constant over a period of a couple of centuries. Any attempts to associate them with the superficial aspects of the Earth's crust must be unsuccessful, for the continents, oceans, mountain ranges, etc., have remained essentially constant throughout many centuries while both the rate of secular change and the field due to non-uniform magnetization vary considerably. These remarks do not apply to local anomalies--irregularities in the magnetic field extending over a few square kilometers--which are unquestionably associated with geological structure near the surface such as ferromagnetic deposits. It is not likely that secular change alters the general features of these local anomalies.

In the absence of a satisfactory theory to explain the Earth's magnetic field, the abovementioned changes in that field must also remain unexplained. On the hypothesis of a ferromagnetic Earth, secular change would indicate changes in intensity of magnetization. Such changes might be caused by large masses of the Earth's substance rising above or falling below the Curie-point temperature. That masses of ferromagnetic matter great enough to produce these effects may exist in the 20-km surface layer seems unlikely. Secular changes in the Earth's magnetism, then, are indicative of great and relatively rapid changes occurring deep within the Earth such as are not suggested by other geophysical sciences and are not consistent with the comparatively static picture of the Earth which seems quite generally accepted. Efforts to discover magnetic changes attributable to earthquakes have met with no success.

The ephemeral fluctuations of the Earth's magnetism--diurnal variations, magnetic storms, etc.--originate above the Earth's surface. These fluctuations in the magnetic field induce currents within the Earth which in turn produce magnetic fields differing in phase and amplitude from the primary inducing fields. The secondary fields have been separated from the primary fields by spherical harmonic analysis and found to contribute about 30 per cent of the fluctuations.

The theory connecting the induced currents with the inducing magnetic field was first investigated by Lamb [12] and its development has been continued by a number of other investigators [13]. Briefly stated, in the case of the diurnal variations where each term of the spherical harmonic series corresponds to a periodic fluctuation the phase-difference between the primary external field and field of the secondary currents induced by it is determined by a function involving the product of the conductivity and the square of the radius of the sphere in which the currents are flowing. The function determining the relative amplitudes of the primary and induced secondary magnetic fields of the variations also involves this product and contains a factor q^{2n+1}, q being the ratio of the radius of the conducting sphere to the radius of the Earth and n the degree of the particular harmonic term involved. If it is assumed that the radius of the conducting sphere is identical with the radius of the Earth, no value can be inferred for the conductivity which brings the phase-differences and the amplitude-ratios into agreement for all of the harmonic terms. If the conducting sphere is taken as smaller than the Earth, a value for its conductivity and for its radius can be inferred which bring the phase-differences and amplitude-ratios into agreement for all harmonic terms. The radius of this conducting sphere is some 200 or 250 km less than the radius of the Earth and its conductivity about 4×10^{-13} electromagnetic cgs unit. The layer above this sphere is very much less conducting. These conclusions were reached on the assumption that the magnetic permeability of the Earth is unity. Greater values of permeability would have led to greater values of conductivity.

This inference from the terrestrial-magnetic variations should not be regarded as a mere hypothesis--it is compelling conclusion from classical electromagnetic theory and observational facts. The diurnal variations supply no information concerning electrical conductivity at much greater depths because the currents produced at this depth restrict penetration of the primary inducing magnetic field. The main variations during magnetic storms are aperiodic in character and last for several days. Their magnetic fields penetrate to greater depths and indicate an electrical conductivity of an order of magnitude greater than the above figure, or 4×10^{-12} electromagnetic cgs unit, which is about two orders of magnitude greater than that observed for surface-rocks. None of these phenomena supplies information pertaining to the electrical conductivity at depths of 1000 km or more. No other evidence for a discontinuity at a depth of 200 km is known, nor do the magnetic data imply that the discontinuity is a sharp one.

The significance of this inference invites speculation. If the electrical conductivity increases at a depth of about 200 km, a similar increase in the thermal conductivity might be expected from the Wiedemann-Franz relationship, although this relationship does not necessarily hold since we are ignorant of the nature of this electrical conductivity. If, like the electrical conductivity, the thermal conductivity at these depths is two orders of magnitude greater than that of surface-rocks, assumptions (2) and (4), previously mentioned, by means of which temperatures have been assigned to various depths, do not hold.

Cooling would have proceeded by convection until the thermal gradient equalled the variation of melting-point with depth. Greater conductivity below the 200-km depth would result in more heat being conducted to the boundary-region than away from it. Thus the 200-km layer of the crust could never entirely solidify until the thermal gradient below 200 km was one-hundredth the gradient above it. Under these conditions solidification of the Earth would have proceeded from the center, in agreement with the view held by Adams [14].

Conditions when convective cooling ceased and conductive cooling began on the basis of these inferences are purely conjectural. It might be supposed that the change in mode of cooling occurred when the surface-temperature was 1400° C and the temperature at 200 km was 2000° C, allowing for an increase of melting-point with depth of 3° per kilometer. Below 200 km the thermal gradient would be one-hundredth as great, giving a temperature at the Earth's center of 2200° C. This implies the assumption that before solidification of the crust took place sufficient time had elapsed to permit extensive conductive cooling of a solid core, heat being carried away from the surface of this core by convective currents in the still-liquid crust.

From such initial conditions conductive cooling of the entire mass would have proceeded in much the manner indicated by the several solutions of the problem. Appreciable cooling would have occurred at greater depths than is usually considered. The mathematical treatment is more involved and may require the recognition of the Earth's spherical form. One must not be unmindful of the effect of radioactivity in supplying heat lost through the surface, nor of the thermal gradients observed in wells. Recent observations indicate that the "normal" geothermal gradient may be considerably less than is commonly accepted [15]--10° C per km instead of 30° C per km. Accepting values given by Jeffreys [16] for radioactivity and heat-conduction of the crustal rocks, this new value of the gradient could be maintained by the radioactivity of a layer of granite 10 km thick with no radioactivity below it. This is the thickness of the granitic layer as indicated by seismological evidence.

These speculations on temperatures of the Earth's interior are more consistent with the hypothesis that the Earth is ferromagnetic. Although it does not seem likely on this basis that the entire substance of the Earth is below the Curie-point temperature, assuming independence of pressure it is reasonable to suppose that a quite appreciable portion could be in a ferromagnetic state. With the suggested temperatures for the center, a rise in Curie-point temperature of less than 0°001 C for a pressure-increase of one atmosphere would permit the hypothetical nickel-iron core to be ferromagnetic. A dependence of Curie-point temperature on pressure of this magnitude is less than the limits of accuracy of the experiments by Adams and Green, previously mentioned. With fairly low temperatures down to considerable depths, large masses of material could participate in changes in magnetic state and account for the phenomena of secular variation.

To summarize--Absence of any satisfactory theory to account for the Earth's magnetic condition consistent with the view that the interior of the Earth is at a high temperature calls into question the validity of the temperatures assigned to it. Secular change indicates that large fluctuations occur in the magnetic condition of matter at great depths which progress rapidly with respect to geologic time. These changes are not consistent with the view that the Earth's interior is static. Study of the magnetic fields arising from electric currents induced by diurnal variations and magnetic storms leads to the inference that at depths of 200 km the electric conductivity increases greatly relative to that of surface-rocks. If the thermal and electrical conductivities follow the Wiedemann-Franz relationship, temperatures of the interior of the Earth may be considerably lower than is ordinarily supposed. Speculations in this connection suggest that the temperature at the center of the Earth may have been as low as 2200° C when convective cooling ceased.

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THE BEHAVIOR OF MATTER UNDER EXTREME CONDITIONS

P. W. Bridgman

The "extreme" conditions of the title are conditions of stress attainable in the laboratory; the temperatures involved do not usually reach higher than 200° C. A number of experiments have been made in which shearing stresses sufficient to produce plastic flow have been applied at various pressures up to 50,000 kg/cm^2. The magnitude of the shearing distortion produced in these tests is greater than that attained under ordinary conditions, the displacement in shear of one row of atoms tangential to the next row being of the order of tens of thousands. Furthermore, the plastic strength, or the force required to produce plastic flow, is usually many fold greater at 50,000 than at atmospheric pressure. This means that at 50,000 it is possible to study the effect of much greater shearing stresses than are realizable under ordinary conditions.

Under these conditions any crystal structure originally present is reduced to microscopic size. Copper, for instance, becomes after shearing so fine-grained that only a single very diffuse X-ray line is obtained on X-ray analysis. Some grain-growth has been observed to take place in copper very slowly in time. Other materials with lower melting-points may show very much greater grain-growth. There is no evidence that a truly glassy state is produced after exposure to extreme flow; the conditions of the experiment were such that it was not possible to say whether the condition may have been glassy while flow was occurring. Substances which are originally glassy may flow plastically in the same way as crystalline substances.

The force required to produce plastic yield is for most substances sensibly the same whether yield is rapid or slow. Substances near their melting-points, however, may exhibit more or less dependence of shearing force on speed of yield.

Most substances yield to shearing stress by plastic flow. A small proportion may also yield by fracture, that is, rupture along the shear-surfaces, with a finite displacement tangential to the surface, with subsequent seizing and complete healing of the fracture if the shearing stress drops sufficiently during the displacement. In most cases this fracture is connected with the speed of shearing displacement, and occurs less frequently and sometimes vanishes completely if the velocity of shear becomes low enough. On the other hand, there are a few substances which show no trace of plastic flow under shearing stress, but yield only by fracture. Examples have been found both of crystalline substances (graphite) and glassy substances (quartz glass) which yield only by fracture. Of course, it is not possible to establish by laboratory experiments that, if deformation were of geological slowness, these substances also might not be capable of plastic yield.

Various chemical effects may accompany plastic flow at high pressures. Reductions of oxides to the metals and synthesis of sulfides are among the effects observed. Professor Larsen has recently cooperated in an attempt to synthesize some of the so-called "shear" minerals from their probable components. These experiments were all made at room temperature, in the presence of water. The very difficult microscopic analysis was done by Professor Larsen. In no case was the expected synthesis certainly accomplished, probably the temperature being too low. The most striking result of the shearing stress was the complete welding to a transparent glass-like mass of material which originally was in the form of fine powder. However, the substance was not a glass on the molecular scale, because the index of refraction was approximately the mean of the indices of the original crystalline material, whereas the index of a glass would have been considerably lower. This complete welding is a universal effect of exposure to high shearing stress.

In addition to the experiments on the effects of shearing stress at high pressure, a number of measurements have also been made with pure hydrostatic pressure up to 50,000. The experiments have so far been confined to phase-changes and compressibilities. Phase-change between solids, or polymorphic transition, is a very common phenomenon at high pressures. The volume-changes may range up to ten per cent. If the number of examples is plotted on a logarithmic scale against the change of volume, a roughly uniform distribution will be found from the maximum down to volume-changes so small as to be beyond the sensitiveness of the measurements. This suggests that the number of examples will still further increase when the sensitiveness of the measurements is increased. It is also practically certain that the number will increase when the temperature is raised sufficiently close to the melting-point. Phenomena of viscous lag or of complete suppression of a transition are very common; many transitions which will not run at room temperature run readily a hundred degrees higher. Plastic flow is very effective in preventing lag phenomena.

The shearing strength of the modification stable at high pressures may be greater or less than that of the low-pressure modification; the compressibility of the high-pressure form is usually somewhat greater than that of the low-pressure form.

At high pressures the "ice" type of transition, that is, a transition in which the phase stable at higher temperature has the smaller volume, tends to become more frequent than at low pressures, nearly 50 per cent of the new transitions between 12,000 and 50,000 being of this type, whereas only about 20 per cent were of this type below 12,000. The latent heat of solid-solid transitions at high pressures tends to become unimportant compared with the mechanical work of the pressure acting through the change of volume. That is, the internal energy of the high-pressure phase is almost always greater than that of the low-pressure phase.

Melting under pressure has not yet been studied beyond 12,000 kg/cm^2 except in the case of water and mercury, and then only to 25,000. The melting of mercury at 75° takes place at a pressure which is almost exactly on the curve extrapolated by constant second differences from results to 12,000. I see at present no reason to anticipate any strikingly novel result at high pressure. That is, the best methods of extrapolation which we have at present indicate that the curve will rise smoothly, probably according to some such formula as that of Simon, with continually decreasing difference of volume, the factor which multiplies the change of volume to give the energy-difference between liquid and solid becoming numerically larger, and being of such a sign that the energy of the high-pressure phase (the solid) is always less than that of the low-pressure phase (the liquid). In this latter respect melting is the opposite of a transition between solid phases.

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DISCUSSION FOLLOWING SYMPOSIUM

H. F. REID: Does increased pressure increase the resistance to elastic shearing? Does increased pressure increase the strength of the material to shearing rupture?

P. W. BRIDGMAN: I understand the first question to refer to the ordinary rigidity below the elastic limit. The shearing experiments to which I referred give no direct evidence on this point, but other experiments in which I have been interested indicate that the rigidity increases under hydrostatic pressure by a small amount of the same order of magnitude as the change of compressibility with pressure. In answer to the second question, the shearing strength of normal materials is usually greatly increased by hydrostatic pressure. This increase may run up to factors of ten or twenty, or even more, for pressures of 50,000 atmospheres.

T. S. LOVERING: In connection with the paper by Dr. Van Orstrand, has the question of conductivities been considered? Was not the apparent relation to gravity really the relationship to the high conductivity ordinarily characteristic of deep rocks? For instance, when the highly conductive salt is up close to the surface, the curves correspond closely to those found where granite is close to the surface. Yet over salt we have a negative anomaly and over granite we have a positive anomaly. Have you gone into this matter of conductivity?

C. E. VAN ORSTRAND: It appears that gravity-anomalies are not always negative over salt-domes. Those cases in which they are negative constitute an exception to the proposed correlation of temperature-gradients with gravity-anomalies provided the cap-rock has not been removed. Removal of the cap-rock would probably change a geothermal "high" into a geothermal "low" so that the relation would still hold. Furthermore, the area covered by a salt-dome is very small in comparison with the surrounding area in which there are no domes; consequently, even in the case of failure over the dome, the relation may hold over most of the area represented.

N. H. HECK: I would like to ask Father Macelwane whether the fact that his map showed deep-focus earthquakes along the Aleutian Islands and off the coast of Central America and Mexico indicated that we might expect to find deep-focus earthquakes in all parts of the belt surrounding the Pacific eventually.

J. B. MACELWANE: I am afraid any answer that I would give would be speculation. The only impression that I can draw from the recent earthquake-occurrences is that we have more regions in which deep earthquakes are observed to occur than was supposed a few years ago. It does appear from that map that we have deep-focus earthquakes along the greater part of the west coast of the American Continent and down the east coast of the Asiatic Continent, but what their relationship is in detail to the normal earthquakes I do not think we are in a position to say. There is a center that is related to the eastward projection of what might be called the rim of the deep Pacific. South of the Fiji Islands there is a center of very deep earthquakes. It is geographically far out in the Pacific, but whether it is geologically in the center of the Pacific is another matter.

P. W. BRIDGMAN: With regard to the first suggestion of Father Macelwane that an explosive change of state might be the cause of deep-focus earthquakes, and which he associated with my name, in the first place I disclaim any responsibility for this theory. I can see no reason why there is any necessity for assuming an explosive progress of the transition. It seems entirely conceivable that the transition might progress slowly over a long period, building up stresses because of the change of volume, with explosive release of this stress when the rupture-point is reached.

J. B. MACELWANE: I am glad that Professor Bridgman raised that question. I stated that hypothesis as somewhat based on the work of Professor Bridgman and not having originated with him. I think it is an unfair inference from his work, but it has actually been proposed as though based on it and I really feel that Professor Bridgman's work is much more a confirmation of the third hypothesis I gave of a gradual change of state which eventually results in overstrain and final yielding. I think that hypothesis would be a much fairer inference from his work than the other which has been proposed.

A. C. LANE: There is a correlation between these papers. The magnetic paper suggests that the temperature does not get so hot. I have sat on a big chunk of magnetic ore and had a man walk around it with a compass. Everywhere he went the compass turned toward me. A geologist made some experiments with the magnet near the ground and upon a derrick. If you put your compass right on the surface of the rock, you find positive and negative poles scattered over it. About how low must the temperature be in order to get any magnetic shell? And how far down or deep must that temperature be? Apparently we must have a shell that is not too hot to be magnetic and strong enough so that it can occasionally have stresses. How cool must it be in order to give us a magnetic shell?

A. G. McNISH: As to how cool the Earth must be to have a magnetic shell, we do not know. The experiments indicate that the temperatures which are supposed to exist in the Earth in accordance with the best opinions on the subject are too high to be ferromagnetic, and if the experiments are repeated they may show a slight change of Curie-point which would permit ferromagnetism to exist if one cools the Earth somewhat. It is impossible to ascribe the Earth's magnetism to a thin surface-layer because no such magnetization exists in the surface-rocks except in isolated cases such as magnetite.

Regarding the stratosphere, the measurements which are made in the surface of the Earth are taken in places which have been surveyed to show freedom from anomaly, such as the rock you were sitting on. These measurements uniquely define the Earth's field in the stratosphere up to some region of the ionosphere where electric currents may flow and for practical purposes they determine the Earth's magnetic field throughout space as has been shown by its effect on cosmic rays.

A. C. LANE: I should like to inquire how large the changes were which resulted from the magnetic storm recently reported and if that caused any secular change.

A. G. McNISH: It has resulted in a change of field of about two or three per cent. But after the storm is over, everything is back to normal and that is due to forces outside of the Earth. Changes which occur during storms like that permit the electrical conductivity of the Earth to be calculated.

M. K. HUBBERT: Mr. McNish's vector-map of the Earth's magnetic field shows regions of large magnetic vectors which appear to be fixed geographically. Does this mean that the Earth's magnetic poles are now considered to be fixed geographically, instead of precessing about the Earth's geographical poles with the secular variation of the magnetic elements, as heretofore supposed? Would this vector-map remain constant or change as a function of time?

A. G. McNISH: We have no good evidence for believing the uniform magnetization of the Earth changes. It may or may not change. There is evidence of local change which in the past 37 years has amounted to ten per cent of the maximum amount of the uniform field at the poles. It is impossible to conceive that these are going on in one direction for any great length of time. If that 6000-gamma anomaly in the middle of the Atlantic Ocean continues to go on very many years, the south magnetic pole will be there in 10 times 37 years. It does not seem reasonable to suppose that terrestrial-magnetic measurements are confined to that time in the Earth's history when the magnetic field is most simple and uniform. Observations show that secular change has changed. Nothing is constant about it except continual change.

J. B. MACELWANE: Did I not understand that the requirements that would be introduced by restricting the magnetization to a shell would be beyond that we ordinarily could conceive of any of the materials that we observe at the surface of the Earth and that we should need permanent magnetization in the core of the Earth?

A. G. McNISH: One does not have to have the whole core but certainly more than a 15- or 20-km shell in a magnetic state. If we have a shell of steel 15 km thick and magnetize it, we could not produce a field like that of the Earth because the demagnetizing force at the pole would be much greater than that in the equatorial regions. This would cause greater magnetization in equatorial regions and would produce harmonics of higher degree which would quite overwhelm the first-degree harmonics of the uniform field.

J. B. MACELWANE: It is particularly interesting to me because in my mind the question of the state of the core--liquid or not--is an open question. There is seismological evidence on both sides and the suggestion that the core may have temperatures low enough for ferromagnetism is intriguing. Could we say that we have really conclusive evidence of any kind for high temperatures in the Earth?

F. W. SOHON: Is it quite clear that the seismologist uses the term "core of the Earth" in the same sense in which the magnetician uses it? The seismological core is a small core in comparison with the sphere which the magnetician calls the core of the Earth. In that sense the interior core might be a liquid surrounded by an outer core constituting the major portion of the Earth which would be very rigid and which would have ferromagnetic properties.

A. G. McNISH: What I mean by the core is that region which is about 3000 km or so in radius and which is assumed to be a nickel-iron substance. I was speaking about the thin crust--the portion which I believe is sometimes referred to as the lithosphere--that part 15 or 20 km deep.

A. C. LANE: Outside we have our first shell at about 35 to 50 km. Then we get a maximum of our deep-seated earthquakes at 500 to 700 km. Could that layer between 100 and 1000 km down be due to magnetic rock and how cool would it have to be?

A. G. McNISH: I cannot answer the question on temperature of the Earth which would be required for ferromagnetism. It seems that such a region might be adequate to explain the field because in a shell about 1000 km thick you would have about one-half the matter of the Earth and you would not have to have the high magnetization for such a region that would be necessary if the Earth's field originates in the thin 15- or 20-km crust.

F. E. WRIGHT: With reference to the suggested rise in the Curie-point of $0\overset{\circ}{.}001$ C per increase of one atmosphere pressure, the experimental evidence obtained by L. H. Adams and J. W. Green does not appear to support the assumption. The conclusion drawn by Adams and Green from their measurements reads: "Although the results show minor inconsistencies, they demonstrate that the effect of pressure on the inversion-point is practically nil, but the possibility of a slight decrease in temperature with increasing temperature is not excluded." Under the circumstances, it would seem that the measurements should be repeated in an effort to obtain results of greater accuracy. Too much emphasis should, however, not be placed on the Curie-point itself in view of the discovery by Dr. Bridgman that, with increase in pressures from 12,000 to 50,000 atmospheres, the number of polymorphic modifications is greatly increased. At extremely high pressures new ferromagnetic modifications and shifts in the degree of ferromagnetism in different materials may also be possible and should be investigated when it becomes possible to do so with further development of experimental technique.

A. G. McNISH: The experiments were conclusive that the Curie-point does not change sufficiently for ferromagnetism to exist deep within the Earth if the temperatures usually assigned are valid. However, the technique available at the time Messrs. Adams and Green performed their experiments did not permit sufficient precision to conclude that a change of $0\overset{\circ}{.}001$ C per atmosphere did not occur, which, with the new temperatures suggested, would be adequate for ferromagnetism. If Dr. Adams is here, I should like to have him comment on my statement.

L. H. ADAMS: I think that is true.

O. H. GISH: In the paper dealing with the magnetic evidence that bears on the physical condition and structure of the interior of the Earth, one point depended upon the relation between thermal and electrical conductivity known as the Wiedemann-Franz-Lorenz law. That relationship has been found to hold right well in the case of good conductors. However, much of the material in the Earth is doubtless a different sort of conductor--a semi-conductor--and there may be a question as to whether for such conductors the thermal and electrical conductivities stand in the same relationship implied by the Wiedemann-Franz-Lorenz ratio. One would also like to know whether pressure affects the relation, as was found by Bridgman for good conductors, and whether that effect is positive or negative.

P. W. BRIDGMAN: As to the reasonableness of assuming the Wiedemann-Franz relation between electrical and thermal conductivities, I think that this is extremely hazardous because the Wiedemann-Franz relation applies when the electrons which conduct the electrical current also make the major contribution to thermal conductivity, whereas this condition almost certainly does not apply to the materials in the Earth's crust in the region discussed by Mr. McNish because the absolute value of the electrical conductivity is very low. I wish to call attention to a formula for thermal conductivity: $K = 4.04 \times 10^{-16} v\delta^{-2}$ (P. W. Bridgman, Proc. Amer. Acad. Arts Sci., v. 59, p. 165, 1924), where K is thermal conductivity, v is the velocity of sound, and δ is the mean distance of separation of centers of molecules. This formula should apply approximately to conditions in the Earth. v is known from seismological data, so that the order of magnitude of K should be calculable.

E. TELLER: In discussing the effects of high pressure (higher than a few thousand atmospheres) it is necessary to discriminate between relatively low pressures which introduce into the electronic motion of the atoms or molecules a small perturbation and high pressures which change the electronic structure essentially. The transition between these relatively low and relatively high pressures will occur when the work of compression becomes comparable to the electronic energy in the outermost shells, that is, a few electron-volts.

In the low-pressure region the pressure will vary exponentially with the change in volume. This is so because the pressure arises--at least for atomic or molecular lattices--from the interpenetration of closed electronic shells and in the outermost part of an atom or molecule the electron-density falls off exponentially.

For extremely high pressures the pressure will change with the inverse 5/3 power of the volume, that is, at such pressures the compressibility will decrease less rapidly than in the low-pressure region. The volume-pressure relation for high pressures follows from the Pauli principle, the application of which to matter of high density requires the electrons to have very high average kinetic energies. They will, therefore, move with practically uniform velocity and their pressure can be calculated in a simple way.

Extrapolating the measured compressibilities with the help of the exponential (low-pressure) formula one finds that at around a million atmospheres the work of compression becomes great enough to cause an essential change in the electronic structure. Matter in the core of the Earth is in this transition-region in which all physical and chemical properties will begin to change strongly. One can not hope, therefore, to get correct information about the properties of matter near the center of the Earth by extrapolating measured properties to such high pressures.

M. A. TUVE: For which materials will the transition-region set in at the lowest pressures.

E. TELLER: If compressibility is high and ionization-energy is low, the transition-region may start at a few hundred thousand atmospheres. For heavy elements both of these requirements are frequently fulfilled, and for them the transition may be expected to set in rather sooner than for the lighter elements.

M. A. TUVE: What are the magnetic and electric properties of matter in the transition-region?

E. TELLER: It is difficult to predict the properties of matter in the transition-region. One may expect, however, that matter at such high pressures will not tend to be ferromagnetic because, according to the Pauli principle, electrons occupy least space if their magnetic moments neutralize each other. But exceptions are still possible at pressures around a million atmospheres. One may expect that in this pressure-region electron-conductivity (giving high electrical conductivity) sets in for every material, since the outermost atomic or molecular electron-shells will be destroyed through the pressure and the electron-structure will resemble that of the metals.

SUMMARY OF THE PRECEDING PROGRAM

L. H. Adams

I am glad to have the opportunity, upon Chairman Heck's invitation, to comment on the subject of this symposium, although I feel that time does not permit an adequate summary. The first thought that occurs to me is one of gratification that there exists, in the American Geophysical Union, a medium for exchange of thought on a broad subject such as this. Those who recall the early days of the American Geophysical Union, in which it existed as a small committee of the National Research Council and in which the annual meetings were devoted mainly to a formal report from the chairmen of the various sections, will note with especial pleasure the development of the Union into an active and alert society. Probably there exists no other organization, at least in this country, where all the great problems presented this afternoon can receive the interest and appreciative hearing that are now afforded.

Possibly the first impression of one listening to this program is that the whole subject is a hopeless puzzle. Important evidence on the one hand shows that the interior of the Earth is very hot, while on the other hand various considerations demonstrate that it is comparatively cold. We have important evidence that the material of the interior is weak, while other observations prove that it is quite strong, that is, resistant to plastic deformation. One set of observations indicates that the interior of the Earth must be magnetic, while another set of facts indicates that it can not possibly be so. Important observations show that the condition of the interior is a static one, and other facts seem to prove that it must be in motion. Viewing the subject more optimistically, the present discussion has at least defined the problems and has pointed out the proper directions in which further investigations should proceed.

The word "extrapolation," used frequently in the course of the program, deserves special comment. Since it is obviously impossible to tunnel through the Earth, even if some one were to promote such a project and obtain the money for it, future progress will have to depend largely upon extrapolation of some sort. The dangers of extrapolation are well known and some of the difficulties have been pointed out by the speakers. Nevertheless, it will be necessary to extrapolate laws and relations beyond the region of experiment. In order to do this it is imperative that laboratory measurements be made under extreme conditions--at high temperatures and at high pressures, in order to approach the conditions existing within the Earth, and also at very low temperatures because in this region the laws of physics take on a more simple form and become more easily verified. We must also take full advantage of our mathematical tools, devising new ones when necessary and sharpening up those which we already possess.

The present program has one feature in common with most other programs of scientific papers. It emphasizes the need for further data. We need more measurements of temperature-gradients, especially in formations consisting of igneous rocks, and we should be prepared to take advantage of any opportunity to make measurements in a deep well drilled in an undisturbed region in which the sediments are of negligible thickness. Many more measurements of gravity are required, with accuracy as high as possible and with stations closely spaced. As already pointed out, there is a special need for more seismologic data and for further extensive observations on the magnetic field of the Earth.

Among the greatest questions that confront us today are the origin of the Earth's magnetic field, the cause of deep-focus earthquakes, and the mechanism of regional subsidence. A great number of the other subjects of geophysical inquiry are a part of, or related to, these unsolved problems. It seems to me that this program has demonstrated that further progress, as implied by the title of the symposium, will depend upon attention to the theoretical as well as the observational considerations; it has indicated clearly the necessity for both field- and laboratory-experimentation.

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NOTE ADDED MAY 28, 1937, BY A. G. McNISH ON THE EARTH'S INTERIOR AS INFERRED FROM TERRESTRIAL MAGNETISM--In invoking the Wiedemann-Franz relationship to infer the thermal conductivity of the Earth at great depths the writer was aware, as Dr. Bridgman pointed out, that this procedure was hazardous. Attention was called to this in the original article. Discovery of an improved electric conductivity at depths of 200 to 250 km was un unpredicted event which may have no relationship with the thermal conductivity. This fact, however, does argue against the validity of assuming that thermal conductivities of surface-rocks hold at great depths.

Subsequent to presentation of the paper, Dr. L. H. Adams explained to the writer that the variation of melting-point of rocks with depth is probably not linear to very great depths, so that the initial temperatures of the Earth when solidification occurred must have been much lower than deduced from extrapolation of the 3° to 5° per km gradient. This view is more favorable to a lower temperature for the Earth's interior. Dr. Adams also called attention to the slow rate of cooling for a sphere the size of the Earth, even with greatly enhanced thermometric conductivity. Even if the thermometric conductivity is a hundredfold greater than ordinarily accepted values, appreciable cooling at great depths could not have occurred within the time-interval allowed by the radioactive age of surface-rocks. The speculations regarding the temperature of the Earth's interior involved the explicit assumption that appreciable cooling at great depths had occurred before the surface-rocks solidified. The radioactivity data, thus, would set the time at which surface-rocks solidified, while solidification of the interior may have occurred much earlier. To allow sufficient time for appreciable cooling of the interior, the Earth's chronology may have to be modified somewhat. According to Jeffreys, eccentricity of the orbit of Mercury allows an age for the Earth an order of magnitude greater than that given by radioactivity. Since passage of heat through the upper layers would have proceeded by convection, the blanketing effect of the radioactive surface-layers would thus have been nullified. It is important that these points should be stressed.

In offering these speculations it was not the writer's intention to assign new and definite temperatures to the Earth's interior, but rather to cast doubt on the hypothesis that the Earth's interior is at a very high temperature--a view which is difficult to reconcile with numerous other geophysical facts. It seems that those who have studied the matter are less strong in the belief of a very hot Earth than those who have given the matter no consideration.

AMERICAN GEOPHYSICAL UNION

Eighteenth Annual Meeting

SECTION OF GEODESY

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THE EDINBURGH MEETING OF THE INTERNATIONAL ASSOCIATION OF GEODESY

Walter D. Lambert

My real paper is before you in the reprints (English translation) which have been distributed of the resolutions adopted at Edinburgh by the International Association of Geodesy. It is expected that the resolutions will appear in an early number of the Bulletin Géodésique. My comments on them will be few and brief. On many of the resolutions I shall have no comment to make and only in one case shall I make comment not directed towards a particular resolution. Let us take some of the resolutions in numerical order.

1. Formulas, tables, or nomograms to transfer from one ellipsoid to another--The problem needs defining more clearly. If we try to solve it on a continental scale, we find that the change in geographic coordinates between one point and another depends on the route followed. If the problem be considered on a scale less than continental, say for one of our larger states or for one of the countries of Europe, the difference due to difference in route may safely be ignored by adopting some arbitrary convention. Laplace points introduce another complication; the problem is difficult enough without them, if our scale be continent-wide; with them the problem becomes still more difficult. This resolution may be read in connection with resolution 6.

2. This resolution will be considered in connection with resolution 32.

19. Central bureau for isostatic reduction--Such a central bureau has been established at Helsingfors, Finland, under the direction of Prof. Heiskanen, Reporter for Isostasy and author of many publications on the subject. The work of making isostatic reductions is far behind the work of observing gravity and the problem of isostatic reductions of the vertical has hardly been touched. Prof. Heiskanen expects to have the reductions made chiefly by university students. The expenses will be met by payments from those who send in stations to be reduced instead of making the reductions themselves, by a small subsidy from the Association of Geodesy and perhaps by another small subsidy from the Finnish Government. Details are lacking as to just what has been accomplished in the few months since the establishment of the central bureau was voted at Edinburgh but no time has been wasted in beginning the necessary preparatory work.

21. Observations in the Southern Hemisphere--The need of observations in the Southern Hemisphere has been stressed in a resolution adopted at a previous meeting of the Association but the importance of the subject justifies stressing it again.

32. Committee on the Geoid--Strange to say, the Association of Geodesy during all the years of its existence has had no Committee on the Geoid. Now it has one and it is violating no confidence to say that an unusually good set of minutes of its meetings at Edinburgh have been prepared, thanks to the Chairman and the Secretary of the Committee. It seems likely that much of the hard scientific thinking done in geodesy will center around the work of this Committee.

The Committee recommends (32c) the use of the isostatic reduction in determining the geoid. This is a mooted question and there are still dissenters, but resolution 32c was approved both by those who think that isostasy is the general rule and by those who are not so sure of its generality.

Resolutions 32b and 2a and 2b may be read in connection with one another. All have to do with the number of astronomical stations in a triangulation. Resolution 32b recommends a very large number; it would ordinarily mean that every principal triangulation-point would be an astronomical station and that even between these points astronomical stations would be interpolated. Resolution 2, on the other hand, would reduce the number of Laplace points below that used in the current practice of the United States Coast and Geodetic Survey for first-order work and would caution against attributing too great an importance to Laplace azimuths.

There is no real contradiction. For the determination of the geoid, deflection-stations (that is, astronomical stations) must be close together, almost without limit. On the other hand, there is a limit to the number of Laplace points that can be used to advantage in the adjustment of a triangulation, though where the line should be drawn is a matter of opinion.

Because some of the resolutions have not been mentioned does not mean that they are not important. I commend them all to your attention, even those that deal specifically with operations outside the United States.

Most of the real work of the Association of Geodesy is done in committee. If this country is to receive the consideration due it, it must send geodetic delegates. There will be no scarcity of American delegates in 1939, when the meeting will be held in Washington, but we must look to 1942 and beyond and try by every means to see that this country is adequately represented.

The committee method of doing business has one disadvantage. One person may be a member of two or more committees scheduled to meet at the same time and he can not be in two places at once. To remedy this conflict a classification of committees was adopted. How far it will obviate the difficulty mentioned can be determined only by experience.

In conclusion, I say what I have said before: Read the resolutions--all of them--and think them over carefully.

U. S. Coast and Geodetic Survey,
Washington, D. C.

ESTABLISHING HARBOR-LINE CONTROL BY GEODETIC TRIANGULATION

Noel J. Ogilvie

The combined harbors of Fort William and Port Arthur, Ontario, situated as they are, on the north shore of Lake Superior, at the head of navigation on the Great Lakes, rank among Canada's most important distributing, storage, and shipping centers. Facilities exist to permit extensive quantities of coal, oil, pulp, and paper, and especially grain, to be stored at, or shipped through, these ports. Some 27 grain elevators provide a total storage-capacity for almost one hundred millions of bushels. There are between 30 and 40 miles of protected harbor-frontage; Fort William having 25 miles along the banks of a river and its two diverging branches, while Port Arthur has slightly less than ten miles of protected lake-frontage.

The Harbor-Lines of Fort William and Port Arthur, as authorized by Orders-in-Council, are described by metes and bounds, and comprise a series of straight-line courses coinciding with or adjoining private property boundaries fronting on the harbor-lines. Private properties are located on the land-side, while the harbor-line is controlled by the Federal Government, and beyond this line, piers, breakwaters, wharves, and other structures are not to be built.

The Fort William Harbor-Lines follow both banks of the main river and its two diverging branches. With the exception of wide expanses used as turning basins there are miles of comparatively narrow channels dredged to minimum depths of from 21 to 24 feet, depending on location, and with widths ranging from 450 to 600 feet with occasional stretches less than 450 feet in width. On the other hand, the Port Arthur Harbor-Line follows along the shore in front of a series of deep water-lots, thus keeping it at a considerable distance out in the water.

Original harbor-line control-system--The points, where changes of direction of the harbor-lines occur, were often some considerable distance out in the water and therefore seldom if ever marked. Originally many of these points were described as being in the productions of certain land-property boundaries and at specified distances from reference-points thereon. There were instances when those reference-points were not permanently marked. Grounds for doubt arose and discrepancies occurred.

New control-system planned--As time progressed, the importance of shipping handled by these ports, together with the intricacies of between 30 and 40 miles of harbor-frontage, which included the comparatively narrow channels of the Fort William Harbor, where clear rights-of-way had to be maintained by the Federal Government at specified minimum widths and depths, increased the need for a basic survey. Finally, at the request of the Federal Department of Public Works, definite plans were laid comprising the following:

(1) The Geodetic Survey of Canada, as it was called at that time, was to establish a system of distinctively marked permanent harbor-line control-points along the water-front to accurately fix the positions of the harbor-lines.

(2) Local land-surveyors were later to be engaged to establish the harbor-lines on the ice, according to their best interpretations of the Orders-in-Council, and obtain the positions of all points of change of direction along those harbor-lines with reference to the harbor-line control-points by carefully executed closed traverses or by triangulation.

(3) All field-notes were to be reduced by the Geodetic Survey of Canada.

(4) A system of plane coordinates was to be employed, in which the positions of every point, in each city, would be designated by coordinates relative to an established center of coordinates in its own respective city, and plans showing such information were to be prepared and registered.

(5) New Orders-in-Council were to be prepared in which the harbor-lines would be described by plane coordinates instead of by metes and bounds.

Geodetic triangulation--Geodetic triangulation was recognized as the most satisfactory means of establishing the desired harbor-line control-system, since the area under consideration resembled the bottom of a basin, with commanding ground on three sides and a favorably located island on the fourth. These topographical features permitted a few geodetic stations to be established on such commanding sites as would allow the accurate determination by triangulation of the positions of practically every point throughout the area, thereby filling both present and future needs.

So far, the harbor-line and those properties fronting on it have benefited by this harbor-line control-survey, but it is quite apparent that all subsequent public and private surveys within the area will also benefit directly in proportion to the use they may make of the results of this basic survey.

Generally speaking, the triangulation-net was, of necessity, one in which a great deal of overlapping occurred, but by careful selection it was possible to obtain strong figures throughout. For purposes of protection and convenience, stations were, where possible, located on property-boundaries, thus providing extra azimuth-lines for local use.

Geographic control--The latitude and longitude of a station previously established about 1910, and determined on the Clarke Spheroid of 1866 and the North American datum through Canadian Geodetic-Survey triangulation, based upon four United States Lake-Survey stations, one of which is Isle Royale, form the position-datum.

Azimuth-control--Canadian triangulation on the north shore of Lake Superior exists as an isolated scheme and is not yet connected with primary accuracy to the existing first-order schemes to the east and west; for this reason, the geodetic azimuth is discarded in favor of an astronomic azimuth for use in the Fort William and Port Arthur local triangulations. This azimuth was determined in eight positions uniformly distributed on the 12-inch horizontal circle and is accepted, pro tem, for orientation.

Length-control--The length of the line connecting two triangulation-stations on a concrete breakwater, approximately 3935 feet apart, was measured four times and the mean value reduced to sea-level. One forward and one backward measurement were made with each of two invar tapes using the same methods and equipment regularly employed while measuring base-lines for first-order triangulation. Posts, toe-nailed to a base and weighted in position by two pieces of pig iron weighing 170 pounds, served as end supports for the tape, while a smaller post similarly secured in place by one piece of pig iron provided the central support.

Horizontal-angle measurement--Observations for horizontal directions were made by sighting on targets, in daytime, with a 5-1/2 inch Wild precise theodolite employing a minimum of eight positions uniformly distributed on the horizontal circle for the main stations and a minimum of four positions for all other stations. With the exception of cloudy days, observations were made during the early morning or late afternoon and evening. At such times, the targets could be distinctly seen and accurately pointed on with ease, without the boiling and indefiniteness which prevailed during the middle of the day.

Adjustment--For convenience the triangulation was broken up into one main net, and several small dependent nets, and adjusted successively. Calculations were made upon the Clarke Spheroid of 1866, expressed in meters, and logarithmic lengths were referred to sea-level and not to the elevation of the Fort William and Port Arthur Area.

As it is more convenient for general use to have the linear unit in feet than in meters, this alteration is made by applying a factor which includes the correction for increase in length to the elevation of the Fort William and Port Arthur Area, together with the increase for meters to feet.

Plane-coordinate system--Since the Fort William and Port Arthur Harbor-Line Surveys covered a relatively small area, the subsequent calculations are more easily performed upon a plane surface, using rectangular coordinates, than upon the spheroid using latitudes and longitudes. Therefore, a centrally located geodetic station was selected as origin of rectangular coordinates and assigned the coordinates, departure 0, latitude 0; the axis of departure being at right-angles to the geodetic meridian, through the chosen origin, which forms the axis for latitude. All rectangular coordinates are measured parallel to the above defined axes. Bearings at any station within the survey are reckoned clockwise from zero to 360°, the zero-line being a line through the station and parallel to the latitude-axis through the origin of coordinates. Direct and reverse bearings always differ by exactly 180°

For convenience, a table giving corrections to azimuths enables one to secure proper orientation in bearings at all geodetic stations. Likewise, similar conversion-factors of bearing to azimuth for harbor-line traverse-stations have been tabulated.

Results of geodetic triangulation in connection with establishing harbor-line control for the harbors of Fort William and Port Arthur, Ontario, 1935 and 1936

(1) Accuracy of results--The field-results obtained during the seasons of 1935 and 1936 were quite satisfactory, and appear to fully justify the utilization of carefully made targets under similar circumstances wherever accuracy and convenience are of primary importance. For example, during the 1936 field-season alone, some 94 triangles, with lengths of sides ranging from approximately 850 feet to almost 14 miles, were completely observed. The average triangle-error, without regard to sign was 0.75 second of arc with a maximum high of 2.65 seconds. Of the 147 directions considered in connection with the results of 1936, 70 have positive corrections and 77 have negative corrections. The mean of all the corrections without regard to sign was 0.678 second, while the maximum correction was 2.783 seconds.

(2) Stations established--(a) Eleven main net-stations (eight ground-stations and three on grain-elevators) were established in well-distributed commanding positions overlooking the entire area comprising both cities, the harbor-fronts, and the adjoining part of Lake Superior. Two of these main stations, one in each city, were marked by polished concrete monuments to which bronze tablets are to be attached, giving their respective latitude, longitude, azimuth to an outstanding mark, and elevation above sea-level.

(b) Thirty-four harbor-line control-points were established along the harbor-fronts of Fort William and Port Arthur--21 for the former and 13 for the latter--spaced at approximately average distances of 4485 feet and 3100 feet, respectively.

(c) Nine general-purpose geodetic stations were determined, four in Fort William, three in Port Arthur, and two on the Port Arthur Breakwater. These comprised an origin of coordinates for each city together with five points, the positions of which should be beneficial for general surveying and engineering purposes, besides being part of the harbor-line control-triangulation scheme.

(d) Three prominent outstanding points were established suitable as general azimuth-marks for the entire area, comprising one flag-pole, one water-tank, and one lighthouse.

(e) All triangulation-monuments may be used as bench-marks for a precise level-net while several which are located on property-boundaries will provide extra permanent azimuth-lines on the ground.

Targets--Observations were made in daytime using three styles of targets, namely, large, intermediate, and small, depending on the length of line over which the target was to be seen.

(1) Eight-foot target--The intermediate-sized target, commonly referred to as the eight-foot target, was the one in general use, since it was suitable for distances ranging from one mile to eight or ten miles. It comprised a factory-made 3-inch by 3-inch post of thoroughly seasoned Sitka spruce or first-quality clear pine, eight feet high, with two galvanized-iron vanes, two feet square, set at right-angles in appropriate-sized saw-cuts in the vertical axis of the post. The target was kept upright by means of four multi-strand wire-guys fastened to a sheet-metal cap, centered and attached to the top of the post. A metal pin, 3/16 inch in diameter, projecting from the center of the base, served to keep the post centered over a station-mark by merely inserting the pin into an appropriate-sized hole in the center of such mark. Where stations were located on rock or concrete, the multi-strand guys were fastened to small eye-bolts (with nuts in place) cemented into drill-holes. Barring interference by man or beast, a target of this type, when properly placed, could be expected to withstand the effects of the elements for weeks, without failing to retain its original position.

In preparing these targets, the posts and vanes were carefully made and painted to standard specifications. Any vane would fit any post and be rigidly fastened thereto by two 1/4-inch stove-bolts. All targets were similarly painted with horizontal bands of black and white of known widths. This arrangement was very useful when vertical angles were being measured, as it permitted the observer to read off the accurate elevation of his point of sight above the station-mark, and have it recorded, at the same time, as the zenith-distance. In order to protect them from the weather, and to retain a clear-cut appearance, both posts and vanes were given three or four thin coats of white paint on top of which one coat of black was applied as required. In most cases the black-and-white vanes were only used as finders, and a means of positive identification, while the clear-cut black-and-white posts provided appropriate-sized definite marks to be sighted on.

A four-foot bricklayer's plumb-rule was used to insure that targets were accurately plumbed. Turnbuckles placed in each guy permitted fine adjustments to be made as regards proper tension of guys and verticality of the post. For convenience, S-hooks were placed in each guy permitting the target to be temporarily removed during observing operations by merely slackening the turnbuckles and disconnecting the S-hooks.

(2) Ten-foot target--For lines exceeding ten miles in length, or where peculiar circumstances demanded a larger mark, a target similar to the eight-foot target was used, utilizing a 3-inch by 3-inch post ten feet long, and heavy sheet-iron vanes three feet square. This was referred to as the large or ten-foot target.

(3) Plumb-rule target--For lines less than one mile long, the bricklayer's plumb-rule, painted black with a quarter-inch white center line, centered and guyed in position over a station-mark, served as a very satisfactory target. A brass foot-plate fastened to the base of the plumb-rule carried a standard-sized center pin, which, when inserted into the central hole of a station-tablet, retained the base of the target in the desired position. The target was then plumbed by means of its attached plumb-bob. A strip of white cotton two or three feet wide, suspended behind the target, acted as a very convenient finder and background.

Phase--The black-and-white bands on the posts of the targets appeared to eliminate, or at least minimize, the detrimental effects of phase. During periods of bright sunlight, when the white sections of the posts might present irregular shapes, the corresponding black intervals appeared to be true to shape and size, and could be pointed on with ease. With average or better visibility-conditions, there was always a point of sight (either black or white) which could be used with confidence by an observer.

Monuments--All occupiable stations were definitely marked, the method depending upon the location, but in all cases Geodetic Survey of Canada bronze tablets were placed to mark the station-points. For a reasonable period of time it is believed that these stations may be considered permanent, barring wanton destruction or alterations.

In rock--A central tablet was cemented into solid rock and surmounted by a small, bevelled cornered, reinforced, concrete monument, anchored to the rock, and taking the form of a pyramid-frustum with a Geodetic Survey of Canada triangulation station-tablet set in its upper top surface. This monument was 12 inches by 12 inches at the top, 14 inches by 14 inches at the bottom, and one foot high. For convenience, and as a protection afterwards, a galvanized-iron form was used and allowed to remain permanently in place to resist wanton destruction. To allow for the ever-prevalent irregularities in rock-surfaces, the form had a two-inch apron at the bottom on all sides which could be conveniently shaped with a hammer to fit any particular surface. Three bronze reference-tablets cemented into solid rock provided further assurance against the loss of the station.

In concrete--(1) Wharves--A central tablet and two or three reference-tablets were cemented into the top surfaces of wharves.

(2) Roofs--In spite of what one might imagine to the contrary, no difficulty was experienced in obtaining permission to establish geodetic stations on roofs of grain-elevators. A hemispherical concrete monument of 15-inch diameter with tablet was used on all elevator-stations. This marking commended itself to the companies as not liable to cause leaks and not likely to be interfered with in any reroofing program.

In soil--Where soil existed, both a surface and a subsurface tablet were set in the top centers of independent sections of a concrete monument weighing approximately 2400 pounds. This monument, with an overall height of six and one-half feet, comprised a base 20 inches square and four feet high surmounted by a pyramid frustum 12 inches by 12 inches at its top, 16 inches by 16 inches at its base, and 2 feet six inches high with the surface-tablet in its top center, and the subsurface-tablet in the top center of that section of the base of the monument located beneath a horizontal cleavage-plane formed by a sheet of tarred paper placed 15 to 18 inches above the base of the monument.

Provision for finding or relocating stations--A photograph and a standard-sized detailed sketch have been made of each harbor-line control-station to accurately show present-day existing conditions. Copies of these will accompany and form part of the final report on the project.

Geodetic Service of Canada,
Department of Mines and Resources,
Ottawa, Canada

COOPERATION OF THE UNITED STATES COAST AND GEODETIC SURVEY AND THE WORKS PROGRESS ADMINISTRATION IN THE CONDUCT OF GEODETIC CONTROL-SURVEYS

H. W. Hemple

Geodetic control-surveys have been carried on with funds provided by the employment-relief organizations since the inception of this program in each of the states by the United States Coast and Geodetic Survey under the initial Civil Works Administration set-up of November 1933. These surveys consist principally of traverse of second-order accuracy for horizontal control, and the extension of third-order levels to provide for the vertical control. The program is supplemental to the work done by the United States Coast and Geodetic Survey providing for the fundamental control-nets throughout the country, in that it provides a closer spacing of lines of control-stations than are available under the program of the Bureau.

When the change in policy of the Federal Administration in February 1934 stopped Federal bureaus from conducting relief-projects, the United States Coast and Geodetic Survey of necessity lost control of this survey-program. As a result, these surveys were discontinued in many of the states. In some states, however, the local authorities decided to continue such work, and at the present time 15 states have relief-projects sponsored in most cases by local organizations, providing for control-surveys. The officials of the United States Coast and Geodetic Survey have never lost interest in this program, and have cooperated with the State-Geodetic-Survey organizations to the extent of giving advice on technical matters, loaning instruments, calculating machines, trucks, steel towers, tables of logarithms, and providing computing forms which are peculiar to these types of surveys. The Bureau has cooperated further with several of the states by the assignment of experienced officer personnel to the individual state computing offices to act as technical advisers. Where this has been done, computations and adjustments affecting the fundamental Federal nets have been made in such offices, as well as the computations pertaining to the surveys done by the local organizations. Due to the sharp curtailment of Federal funds for carrying on a computing program within the Bureau, this arrangement has permitted the computation of much-needed data pertaining to the fundamental control-nets, which otherwise would not have been completed for several years.

The present regulations of the Works Progress Administration permit of projects being sponsored by Federal bureaus, if the contemplated work is considered as a local project and does not result in employees of the regular establishment being thrown out of employment. Regulations of the Works Progress Administration concerning employment of relief personnel, wages paid, and hours of work per month, must be adhered to. Under these criterions, the United States Coast and Geodetic Survey is sponsoring a computing office in New York City. Four officers and one experienced computer have been assigned to supervise the work in this office.

At present 57 men are employed, most of whom have technical or engineering qualifications. These men are distributed as follows: Twenty-two on leveling; fifteen on triangulation; six on traverse-computations, and the remainder on drafting and clerical duties. To date the following computations have been made: The finally adjusted positions of the intersection-stations for the South Carolina Triangulation; the final positions for the Gastineau Channel (Alaska) triangulation; preliminary positions for 15 arcs of triangulation distributed throughout the country; plane coordinates for the triangulation-stations in Wisconsin; the adjustment of 1450 miles of leveling; and the traverses executed by the Civil Works Administration forces in Indiana. In general, the equations for the adjustments are written by the mathematicians in the Washington office, and these are then sent to the New York office for solution.

In California a Works Progress Administration precise-level party is at present operating under our sponsorship along the Skyline Drive between San Mateo and San Jose. This work is part of the earthquake-investigation leveling which is being executed at periodic intervals to determine the extent of vertical land-movements in this vicinity. We are able to do this work under Works Progress Administration regulations affecting salaries and hours of work, because the operations of the party are in a restricted area and the men are able to live at home, being transported to and from the working grounds each day by automobile.

These two projects are the only ones which are actually sponsored and carried out as United States Coast and Geodetic Survey projects. The other projects which I shall enumerate are sponsored by local authorities and, in most cases, a financial contribution from the sponsor enables the work to be successfully conducted.

In Massachusetts the State Geodetic Survey is sponsored as a Works Progress Administration project by the Department of Public Works. In excess of 400 men are employed, of whom about 60 are in the computing office. During the past year an officer of the United States Coast and Geodetic Survey was assigned to cooperate with this project and supervised the measurement of base-lines at Yarmouth and Wellfleet on Cape Cod, and at Newburyport in northeastern Massachusetts, and the connection of these bases with the triangulation. During the next summer this project will undertake observations on two arcs of triangulation across the State, one at parallel of latitude 42° 00', the other at 42° 45'. The completion and adjustment of the work on these arcs will provide control for much-needed traverse in the western part of the State. To date over 2200 miles of traverse of an average closure of one in 28,500, 3500 miles of second-order leveling, and 2000 miles of triangulation have been completed on this work. Reports issued in book form by this project include among others the following: "Leveling in Massachusetts" in three volumes; "Technical procedure for geodetic surveys"; "Lectures in geodesy" in two volumes; "Tidal bench-marks"; "Projection-tables, Lambert plane-coordinate system for Massachusetts"; and "Plane coordinates for minute intersections of latitude and longitude in Massachusetts."

In Connecticut the State Geodetic Survey project is sponsored by Yale University and is under the direction of Prof. C. J. Tilden. About 127 men are employed on the project, of whom 26 are in the computing office in New Haven. An officer of the United States Coast and Geodetic Survey has been assigned to this project since April 1936. During the past year he has supervised the field-work for a triangulation connection between the work along the Connecticut River and that on the oblique arc. At present an arc of triangulation is being executed to delineate the boundary-line between Rhode Island and Connecticut. Later in the summer it is expected that an arc of triangulation will be run west from Hartford to the New York boundary and when the proposed Hudson River first-order triangulation is completed a connection will be made thereto. The work being done in the computing office under the supervision of our officer consists of the adjustment of the coastal and Connecticut River arcs of triangulation. There are thousands of points whose final positions will be determined as a result of this work. To date about 2500 miles of traverse, 300 miles of triangulation, and 300 miles of leveling have been completed. One publication "Bulletin - Stamford Quadrangle" containing control-data has been issued.

To assist the Georgia Geodetic Survey project, an officer of the United States Coast and Geodetic Survey has been assigned to the computing office in Atlanta. At present about 2400 miles of first-order triangulation are being adjusted in this office. After this is completed, there are about 7000 miles of second-order traverse completed by their field-parties, which will be adjusted thereto. An equal amount of leveling will also be processed. The triangulation-adjustment is about two-thirds completed and the traverse about one-third finished. It is planned to issue these data in the form of a publication to be printed by the Works Progress Administration. The work done by this organization in Georgia has been especially useful to the Soil Conservation Service, and has made it unnecessary for the latter to do any great amount of field-surveying in this State.

In Florida the United States Coast and Geodetic Survey has assigned three men to supervise field-triangulation, and one man to act as technical adviser in the computing office of the Florida Mapping project. About 100 men are employed on this project, of whom 33 are in the office. About 400 miles of steel-tower triangulation has been completed during the past year under the supervision of our men. It is expected that during the next summer an arc of triangulation will be run along the Caloosahachee River necessary for the control of hydrographic surveys. To date about 3500 miles of second-order traverse, and about 3000 miles of leveling have been completed by this organization, and about 1500 miles of this have been adjusted. Publications in prospect to be issued by the Works Progress Administration consist of horizontal and vertical control-data for the three plane-coordinate zones in the Florida system. The one for the northern zone is about ready for issue.

An officer of the United States Coast and Geodetic Survey has been assigned to act as technical adviser to the Arkansas Geodetic Survey located in Little Rock. About 50 men, 25 of whom are in the computing office, are employed on this project. About 4800 miles of leveling for this State and several hundred miles for other states have been computed in this office. Plane coordinates for about 3200 triangulation-stations along the Mississippi River for the states of Tennessee, Arkansas, and Mississippi, and for the San Francisco Bay region, have also been computed. Nine volumes of "Leveling in Arkansas," a compilation of United States Coast and Geodetic Survey, United States Geological Survey, United States Corps of Engineers, Arkansas Geological Survey, and Arkansas Geodetic Survey leveling work, have been published.

In Pennsylvania, at the request of the State Planning Board, one of our officers was assigned to act as technical consultant to the Works Progress Administration control-survey projects operating in that State. There are two projects, one in Mercer County and the other in Bucks County, which are carrying on geodetic surveys. The Mercer County project provides for a triangulation-scheme with stations established at frequent intervals for control of traverse-lines. The objective is the compilation of a property-map from air-photographs, which will be used for tax-assessment purposes. Steel towers, theodolites, and other instruments have been loaned by the Bureau to the project, and two of our former civilian employees are in direct charge of the field-operations.

In Oklahoma we have an officer attached to the computing office of the State Geodetic Survey located at Oklahoma City. This project is sponsored by the Oklahoma Conservation Commission. One officer was also assigned for several months to supervise a precise-level party operated by this organization. This party accomplished several hundred miles of rerunning of our second-order level-lines in this State on which discrepancies were found. The following work pertaining to the Federal nets has been accomplished in the computing office: Adjustment-computations for the arcs of triangulation in Oklahoma and Texas along the 94th, 95th, 96th, and 97th meridians, and along the 37th parallel comprising 1200 miles all told; the field-computations on the triangulation-arcs from Watertown, South Dakota, to Cedar Lake, Minnesota, and from Franklin, Nebraska, to Longmont, Colorado; computations for second-order level-lines in Oklahoma, Texas, New Mexico, Colorado, and Kansas. In addition to this, several thousand miles of traverse and leveling done by the State organization are being adjusted.

In the State of Washington at the present time we have three officers assigned to duty with the King County Aerial Survey project of the Works Progress Administration. This project sponsored by the King County Board of Assessors is for the primary purpose of compiling a tax-assessment map of the county from air-photographs. There are 122 men employed on the project, of whom 32 are engaged in triangulation. The control of which our officers are in charge consists in determining the positions of land-section corners and locating them on the air-photographs. In connection with this project, it is expected that an arc of triangulation will be extended from Seattle to Spokane so that the stations established in King County may be connected thereto and a final adjustment of positions made. King County has an area of about 2200 square miles, the eastern half being mountainous and heavily wooded. The difficulties of executing control in terrain of this nature are very great.

In New Jersey during the past year we have cooperated with the New Jersey Geodetic Control Survey of the Works Progress Administration by assigning an officer to supervise the measurement of a first-order base-line in the vicinity of Elizabeth, and a triangulation-connection between work on the oblique arc done a number of years ago and recent control-work in this vicinity. It is our expectation that shortly a base-line will be measured in New York City and when this is done there will be a readjustment of the triangulation in the metropolitan district and in northern New Jersey, which will give final positions for the stations in this important area.

Geodetic control-surveys have also been conducted by the Works Progress Administration during the past year in the States of North Carolina, South Carolina, Alabama, and Louisiana. We have made no assignment of personnel to these latter projects, but have loaned to them instruments, steel towers, computing forms, and tables of logarithms.

The adjustment of the first-order and second-order triangulation has been completed in South Carolina and the local organization is now computing the final positions on the State Plane-Coordinate System of over 7000 miles of second-order traverse which their own field-parties have completed. About 3000 miles of this work remain to be done.

In Louisiana over 2000 miles of second-order traverse and leveling have been completed. The positions of the traverse-stations are on the State Plane-Coordinate System. The supervisor of the Louisiana Geodetic Survey is following the practice of filing these data in the offices of the engineers for the individual parishes concerned.

North Carolina has been operating a series of county control-survey projects, all under the direction of O. B. Bestor of the Department of Public Works, Raleigh.

In Alabama work has been conducted around Auburn, Birmingham, and Mobile by the Alabama Geodetic Survey under the direction of Prof. J. A. C. Callan of Alabama Polytechnic Institute.

During the past year the Governmental Projects Section of the Works Progress Administration has scrutinized very carefully all projects providing for surveying and is insisting on all city-survey and geodetic control-survey projects being conducted in accordance with recognized standards. Close contact has been maintained between this Section and the United States Coast and Geodetic Survey. The surveys accomplished by the State Geodetic Survey organizations, if of an acceptable standard, will be included in the national net of control. Such surveys will add materially to the total of high-grade surveys throughout the country.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GRAVITY-MEASUREMENTS ON THE U.S.S. BARRACUDA

Maurice Ewing

Introduction

Measurements of gravity at sea, accurate enough to be of value in the problems of geodesy and geology, were first made by F. A. Vening Meinesz in 1923. Since that time Vening Meinesz has perfected his apparatus into a standard form and has made many highly important surveys with it [see 1 of references at end of paper]. The Vening Meinesz apparatus [2] contains three bronze half-second pendulums, all mounted to swing in the same plane. By means of an ingenious optical system, the motions of the three pendulums are combined to give a photographic record of two fictitious pendulums, each fictitious pendulum being independent of small horizontal motions of the apparatus in the swinging-plane of the pendulums. This instrument is installed in a submarine which submerges, when a gravity-observation is to be made, and provides a platform relatively undisturbed by wave-action.

The United States Navy has participated in two expeditions, prior to the present one, for measurement of gravity in the waters adjacent to the West Indies [3, 4]. The cruise described in the present report was made on the U.S.S. Barracuda, Lt. Commander W. A. Gorry commanding. It began November 30, 1936, at Coco Solo, Canal Zone, and ended January 14, 1937, at Philadelphia. The acceleration of gravity was measured at 51 sea-stations and in nine harbors.

The scientific work of the Expedition was done by A. J. Hoskinson, H. H. Hess, and the writer. Dr. Hess supervised the sounding apparatus while Lt. Hoskinson and the writer calibrated and operated the gravity-apparatus.

Method of measurement

The gravity-measurements were made with a standard Vening Meinesz apparatus--the same instrument which was used on the Nautilus Expedition in 1931 [5]. Except for a few innovations, the method of operation was exactly that outlined by Vening Meinesz in his treatise [2]. The innovations are listed below:

(a) Crystal-controlled chronometer--A crystal-controlled oscillator, built by the Bell Telephone Laboratories, was used as constant-frequency source for measuring the periods of the fictitious pendulums. This replaced the balance-wheel chronometers used in previous expeditions. The excellent timekeeping qualities of the oscillator are revealed in Figure 1, which shows the comparisons of the oscillator with NAA time-signals for the entire cruise. The changes in rate of the chronometer shown in the Figure are due to temperature-changes, for the readings have not been corrected for changes in temperature, battery-voltages, etc. This chronometer is not thermostatted and temperatures in a submarine change greatly during a dive. No elaborate control over battery-voltages was used. The cruise started in the tropics and ended in Philadelphia in mid-winter. It is highly significant that the interval between NAA-time and chronometer-time never exceeded 0.6 second during the six-weeks' cruise and that the variation in this interval is very regular. The crystal chronometer has reduced errors in gravity-measurements at sea, due to rate of the chronometer, to the point where they are negligible.

(b) Synchronous motor--The constant-frequency alternating-current supplied by the crystal-controlled oscillator was used to drive a small synchronous motor placed in the light-box of the Vening Meinesz apparatus. An arm driven by this motor eclipsed the light-beam momentarily every half-second, producing narrow breaks in the sine-curves showing the motion of each fictitious pendulum. The period of each fictitious pendulum could then be obtained by the method of coincidences. It was advantageous to thus eliminate the use of relays, etc., between the timekeeper and the pendulum-record.

It was also a great advantage to have the eclipses at half-second intervals, for then a coincidence between crystal chronometer and fictitious pendulum was indicated by an intersection of two sets of eclipses, rather than by the intersection of one set of eclipses with the central axis of the sinusoidal curve of the fictitious pendulum-record.

(c) Time-signal comparisons--For comparison of the chronometer with the radio time-signals from NAA, a Strobotac [6] was used. The Strobotac was arranged so it gave an exceedingly brief flash of light at the beginning of each time-signal. These flashes came once each second, and were used to illuminate a gear in the synchronous motor which made two revolutions per second. The gear was graduated in 50 divisions, corresponding to hundredths of second, and the position of the gear at the time of a light-flash from the Strobotac could be estimated visually with an uncertainty of about 0.001 second.

W. A. Marrison of the Bell Telephone Laboratories, under whose supervision the crystal chronometer was built, suggested this method of comparing the chronometer with the NAA signals. It was also his suggestion that the synchronous motor be placed inside the light-box. All members of the Expedition feel that Mr. Marrison contributed much toward the completion of the gravity-measurements.

(d) Coincidences throughout entire observational period--In previous work with the Vening Meinesz apparatus one chronometer, operating on an electromagnetic relay, has been caused to give momentary eclipses of the light-beam at the start and at the finish of an observation, and a half-second eclipse every second during the middle part of the observation. This permitted coincidence-data to be taken only during the beginning and end parts of the record and phase-data to be taken only during the middle part [2]. In the present work an auxiliary sidereal balance-wheel chronometer was used to give a half-second eclipse on alternate seconds throughout the observation. This permitted both coincidence-data and phase-data to be taken throughout the entire observation if desired. This chronometer was used only for phase-data, and its rate entered in no way into the calculations.

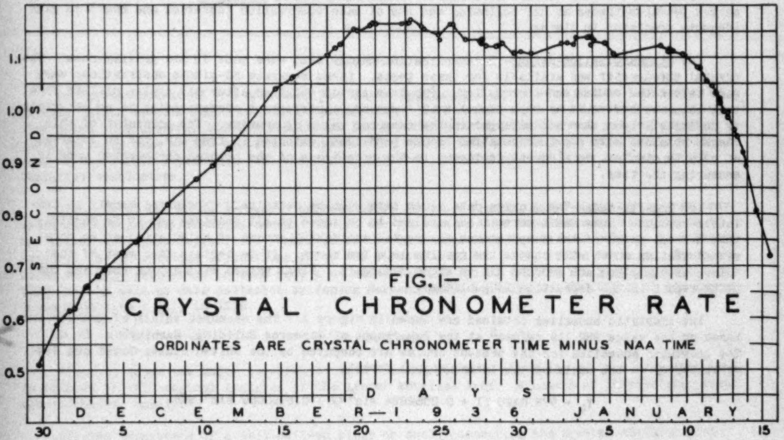

FIG. 1—
CRYSTAL CHRONOMETER RATE

ORDINATES ARE CRYSTAL CHRONOMETER TIME MINUS NAA TIME

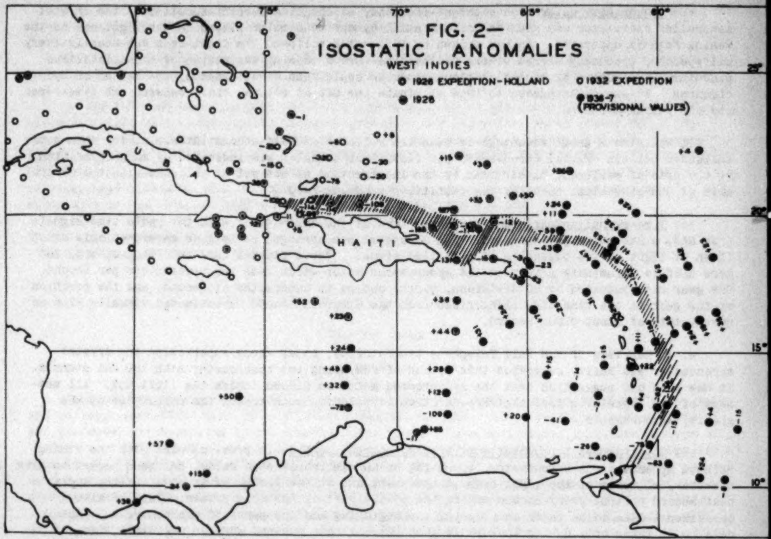

FIG. 2—
ISOSTATIC ANOMALIES
WEST INDIES

Results

(a) Temperature-coefficients--The temperature-coefficient for each of the pendulums was determined in the gravity-room of the United States Coast and Geodetic Survey in August 1936. As the crystal chronometer had not been obtained at this time, radio signals were recorded directly on the pendulum-traces at the beginning and end of each observation (duration one hour) to give adequate precision in timing.

(b) Standardization-swings--Standardization-swings also were made in the gravity-room. The crystal chronometer was available for these tests. Three separate 30-minute observations were made before the cruise and three after. The mean period obtained after the cruise differs from that obtained before it by less than 1×10^{-7} second, a difference corresponding to an uncertainty definitely less than one milligal in the measured value of gravity. The precision of this check, obtained with non-thermostatted bronze pendulums, swinging in free air, for an interval of only 30 minutes, is eloquent testimony to the excellence of the crystal chronometer used in measuring the time.

(c) Gravity-data--The gravity-data given here must be definitely considered merely as tentative results. Some small corrections are yet to be added to all stations and it is possible that a final check of the computations may reveal accidental errors of calculation at an occasional station which will change the results in a few cases. It is certain that most of the values as now given are good to six or eight milligals. Final values will appear when the complete report on the Expedition is published.

The isostatic anomalies obtained are shown in Figure 2. The measured values of gravity are based on the value 980.118 cm/sec^2 at the Department of Commerce Building, Washington, D. C. The isostatic anomalies for the present cruise are computed by the United States Coast and Geodetic Survey on the basis of the international formula

$$\gamma_0 = 978.0490 (1 + 0.0052884 \sin^2 \Phi - 0.0000059 \sin^2 2\Phi)$$

Conclusions

It is seen from Figure 2 that the strip of negative anomalies, which had been discovered north of Haiti and Puerto Rico by the earlier expeditions, extends around the convex side of the Lesser Antillean Arc, having a total length of more than 1200 miles. This negative strip is comparable with that found by the epoch-making survey of Vening Meinesz in the East Indies [1]. The large variations of gravity found in the southern part of the Caribbean reveal a need for more observations in that region.

Acknowledgments

Many organizations and individuals contributed important assistance. The Navy Department assigned the U.S.S. Barracuda to the project, supplied the radio time-signals, and, through the United States Hydrographic Office, handled the general organization of the Expedition. The American Philosophical Society granted funds to cover many of the expenses involved. The Bell Telephone Laboratories designed and constructed the crystal chronometer. The United States Coast and Geodetic Survey assisted in many ways during calibration of the pendulums and made the isostatic reductions for the gravity-stations. The American Geophysical Union, through R. M. Field, Chairman of its Special Committee on Geophysical and Geological Study of Oceanic Basins, rendered valuable assistance in many phases of the work. To all of these, and to the others who helped, we are deeply grateful.

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GEOLOGICAL INTERPRETATION OF DATA COLLECTED ON CRUISE OF U.S.S. BARRACUDA IN THE WEST INDIES--PRELIMINARY REPORT

H. H. Hess

Introduction

During the course of the cruise of the U.S.S. Barracuda a great mass of new data was collected. Since we have just recently returned, these data have not yet had the mature consideration which they deserve, and the results of the gravity-determinations are as yet but roughly known for only some of the stations occupied. Therefore, this preliminary report deals with some of the larger topographic and structural features encountered, and draws certain purely tentative conclusions.

Figure 1 of Dr. Ewing's report, printed above in these Transactions, shows the course traversed and the gravity-stations taken. It was the purpose of this Expedition to concentrate on the Lesser Antillean Region, the remainder of the Caribbean Area having been more or less fully explored on the previous expeditions under the direction of Dr. F. A. Vening Meinesz. These include the S-21 expedition in 1928 [see 1 of references at end of paper], the S-48 expedition in 1932 [2], as well as data collected by Vening Meinesz while crossing the Caribbean on the Netherlands Submarine K-XIII in 1926.

Physiography

Figure 1 shows the major topographic (and also structural, since the two are very intimately related in this region) features of the Lesser Antilles Area. A number of interesting points are indicated, namely:

(1) The occurrence of a well-defined ridge or swell connecting the Greater Antilles with the east-west structures of northern Venezuela.

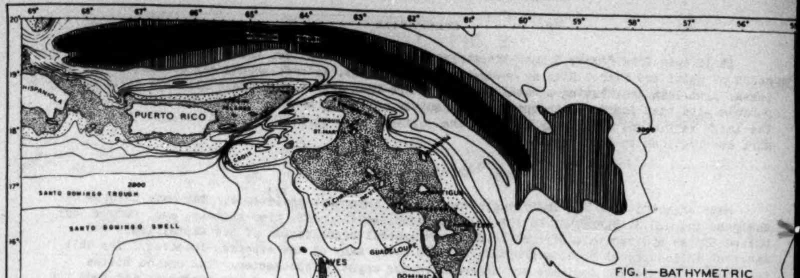

FIG. 1—BATHYMETRIC CHART OF EASTERN CARIBBEAN AREA

69°
68°
67°
66°
65°
64°
63°
62°
61°
60°
59°
58°
57°
56°
20°
19°
18°
17°
16°
15°
14°
13°
12°
11°
10°
9°
HISPANIOLA
PUERTO RICO
CROIX
ST. MARTIN
3000
2000
SANTO DOMINGO TROUGH
SANTO DOMINGO SWELL
ANTIGUA
GUADELOUPE
AVES
DOMINICA
MARTINIQ
TANNER
BASIN
2700
AVES
SWELL
1800
GRENADA
TROUGH
ST. LUCIA
ST. VINCENT
TOBAGO
TROUGH
CURACAO
BONAIRE
GRENADA
VENEZUELA TROUGH
MARGARITA
TOBAGO
TRINIDAD
SOUTH AMERICA
FATHOMS
0-500
-1000
-3000
-4000
-4500
4500+
CONTOUR-INTERVAL
500 FATHOMS
NAVY-GEOPHYSICAL UNION
GRAVITY EXPEDITION
1936-7

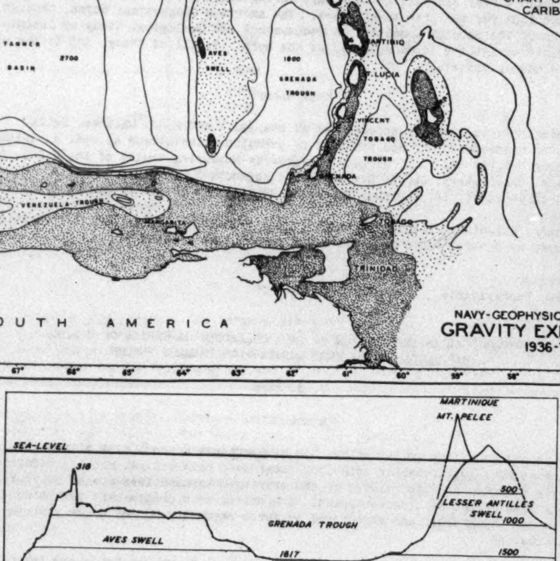

FIG. 2—SECTIONS FROM AVES SWELL TO MARTINIQUE AND ST. VINCENT; VERTICAL EXAGGERATION IS TIMES [DOTS INDICATE SOUNDINGS; NOTE APPARENT SUBMARINE VOLCANOES ON WEST FLANK OF AVES SWELL AND FLAT AREAS ON BOTTOM OF GRENADA TROUGH]

(2) The extension and southeastward curvature of the Brownson Trough, paralleling the Lesser Antilles Arc.

(3) The change of the above feature from a trough to a ridge proceeding southward, the axis of the trough and ridge being the same (Barbados Ridge).

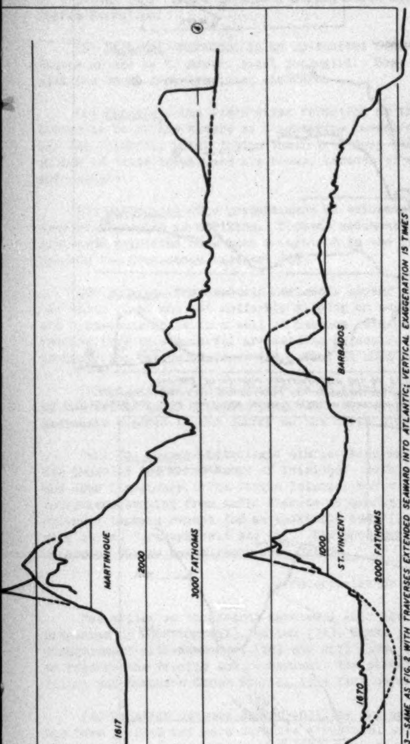

FIG. 3—SAME AS FIG. 2 WITH TRAVERSES EXTENDED SEAWARD INTO ATLANTIC; VERTICAL EXAGGERATION IS TIMES

[NOTE TWO SHARP TOPOGRAPHIC BREAKS WEST OF BARBADOS WHICH MAY BE FAULTS; DASHED LINE ON LOWER TRAVERSE INDICATES POSSIBLE ORIGINAL STRUCTURE GOING UNDER VOLCANO AND ABOUT 3500 FT. BELOW POSSIBLE FILLED BASIN OF GRENADA TROUGH; NOTE ALSO SHARP BREAK AT EAST END OF SAME TRAVERSE WHERE OCEAN-FLOOR MEETS POSSIBLE OVERTHRUST MATERIAL SQUEEZED OUT OF DOWN-BUCKLE; ON UPPER TRAVERSE AT EAST END A PROBABLE LARGE NORMAL FAULT-BLOCK WAS ENCOUNTERED; SHORT TRAVERSE AT END OF MAIN ONE SHOWS SHARP DROP-OFF AFTER TURNING NORTHWARD OVER SCARP, AND DASHED LINE INDICATES OCEAN-FLOOR TO NORTH OF ACTUAL TRAVERSE]

(4) The presence of shallower troughs inside the Arc and parallel to it (Grenada and Santo Domingo troughs), and central basin inside these (Tanner Basin). A peculiar feature of all these is their extraordinarily level floors.

(5) The presence of ridges or swells between these basins. One, the Aves Swell, parallel to the Lesser Antilles, is surmounted on its western flank by a series of peaks, probably volcanoes (Fig. 2).

(6) The bending of the Trinidad structures northeastward and northward to Barbados (there are stratigraphic similarities between the two islands as well).

(7) The occurrence of a probable fault-line along the north side of Anegada Passage (which is considered to be a tear-fault with the south side moving eastward--the topographic depression of Anegada Passage, however, is not attributed to this fault but is only secondarily related to it.)

(8) The presence of a great submarine-canyon at the mouth of Anegada Passage, similar to those along the Atlantic Coast of continental North America. This reaches a depth greater than 2500 fathoms. Another valley probably drains west from the passage into the Caribbean (see Fig. 5).

(9) The occurrence of an east-west fault-scarp at latitude 16° 35' and longitude 57° 51', 5000 feet high, south side up (see Figs. 3 and 4, profile 4).

Geology

Among the main geological observations are the following:

(1) Trinidad--Apparent small northward-moving thrusts occur in the North Range of Trinidad in the section exposed at the Quire River Dam [3]. The overturning and thrusting in the central and south ranges is dominantly southward. If this northward movement in the North Range is general, it gives a broad picture of

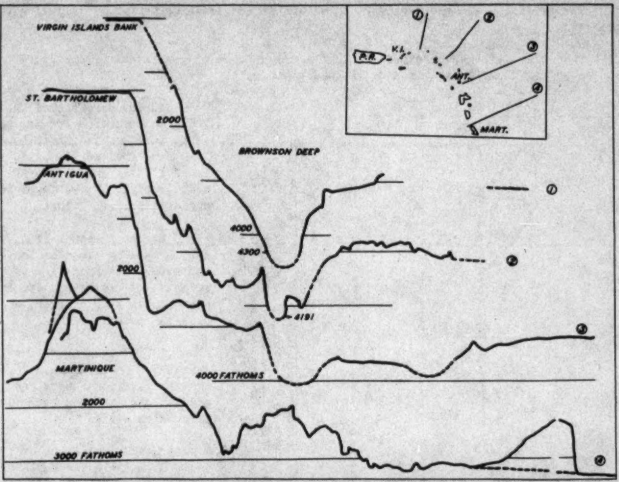

FIG. 4—FOUR TRAVERSES AT RIGHT-ANGLES TO THE NORTHEASTERN PORTION OF THE ARC [NOTE THE CHANGE FROM A DEEP AT NORTH TO A RIDGE ON SOUTHERNMOST OF FOUR; AXIS OF NEGATIVE STRIP LIES ALONG WESTERN WALL OF MAIN DEEP; DASHED PORTIONS INDICATE INFERENCE WHERE SOUNDINGS WERE NOT OBTAINED]

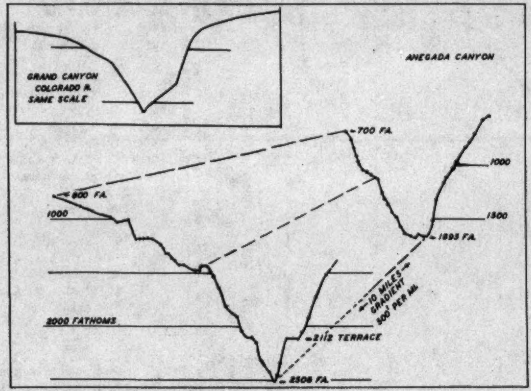

FIG. 5—ANEGADA CANYON COMPARED TO A GRAND CANYON SECTION; VERTICAL EXAGGERATION 8 TIMES

the Island as a two-sided orogen with outward thrusting on either side of a central axis, along which the negative gravity-anomalies lie. The North Range itself and Caribbean Range of Venezuela are probably blocks bounded by east-west rift-faults.

(2) Trinidad--The strikes of formations in Trinidad are dominantly northeast-southwest [4] though the ridges are more nearly east-west. This northeastward trend bends northward to Barbados and does not continue out into the Atlantic as suggested by some.

(3) Tobago--The "gabbros" of Tobago Island are largely altered andesitic volcanics similar to those of the Cretaceous in the Virgin Islands. Volcanic breccias occur on Wolf Island between Tobago and Little Tobago.

(4) Barbados--The Scotland beds are Upper Middle Eocene, and the much-less deformed Oceanics above them are in part as young as Upper Eocene, being equivalent to the Mount Moriah Formation of Trinidad [4]. There is also a strong disturbance in Trinidad immediately preceding the Mount Moriah Formation.

(5) Barbados--Barbados is an up-faulted block. Many small recent faults were pointed out to the writer by H. Huber, local geologist. Some of these appear to be east-west tear-faults with the south side displaced eastward.

(6) Barbados--The Joe's River Formation at the top of the Scotland series appears to the writer to be of the nature of a submarine landslide formed as the bottom sank to great depths, and the Oceanics, which follow them, true deep-sea deposits. Huber, however, does not agree to either of these ideas, and his views, because of broad experience on the Island, should be given more weight.

(7) Martinique--The predominance of volcanic breccias and absence of lava-flows with this type of vulcanism is striking. Miocene sediments are present on the east side of the Island [5]. Limestone xenoliths have been brought up in the volcanic material of Mt. Pelee, probably representing the Cretaceous basement [6].

(8) Antigua--The Cenozoic sediments appear to be gently folded when viewed from the sea off the south coast and not uniformly dipping as suggested by Davis [7]. The presence of an apparent Cretaceous Chalk in a well at Cassada Gardens was pointed out to the writer by W. R. Forrest. Fossils from this material are said to be equivalent to the Craie Blanche of the Paris Basin and probably the Taylor of Texas [8]. That it does not show any sign of metamorphism is surprising.

(9) St. Kitts--"Black Rocks" is an olivine basalt lava-flow. Brimstone Hill is interpreted by the writer as an andesite plug, thus agreeing with Trechmann's views [9, 10]. The upturned sediments exposed in the quarry on the north side of the hill are abundantly fossiliferous.

(10) St. Thomas--Lithologic similarities may be noted between the rocks of the Virgin Islands and those of the North Range of Trinidad. Both include schists of a low grade of metamorphism and blue limestones. The Virgin Islands, however, have abundant andesitic volcanic material and intrusions varying from mafic diorite to quartz porphyries, whereas in the North Range these are entirely lacking except for an andesitic body [11, 4] near the east end of the north coast [formerly called "granophyre," see 12]. The presence, however, of abundant volcanics on the nearby island of Tobago has already been noted.

Interpretation and speculation

The writer is in general agreement with the structural picture of the Lesser Antilles as presented by Woodring [13], Rutten [14], Suess [15], and Dickerson (oral communication), and in disagreement with Schuchert [16] and Hill [17], as to the major relations, and with Hobbs [19] as regards the details and mechanism. The structural continuity of the Greater and Lesser Antilles and northern South America is a fact beyond any reasonable doubt.

(1) Relation between Lesser Antilles and adjoining provinces--On the north, Anegada Passage has been pointed out as a definite structural separation between the Greater and Lesser Antilles. Investigation of the bottom of the Passage shows ridges striking across the Passage in a westerly direction paralleling the strikes in the Virgin Islands. One of these, extending a little northward of west from Sombrero practically crosses the Passage, and its crest was found to be within 25 fathoms of the surface at one place. A similar, parallel ridge lies to the south of this. The depression is thought to be an erosional feature by the writer. It is probably the lowest outlet of the Caribbean, and if sea-level were lower it would be the gap out of which the water of the Caribbean would flow. A probable tear-fault forms the northern edge of the Passage, but it seems likely that it predates the time of the formation of the Passage by a considerable interval. It merely localized the later erosion which formed the Passage. The occurrence of huge fossil rodents on Anguilla [20], closely related to the rodents of Puerto Rico, indicates a land-connection with the Greater Antilles in Pliocene or Pleistocene time. The continuation of the Trough, complementary to the Lesser Antilles Ridge, around from north of the Virgin Islands Bank to east of Antigua, is fairly conclusive evidence of the continuity of the structure of the Ridge itself.

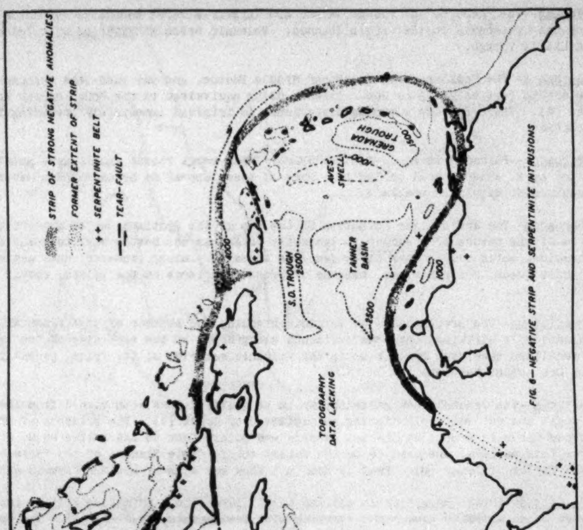
STRIP OF STRONG NEGATIVE ANOMALIES
FORMER EXTENT OF STRIP
SERPENTINITE BELT
TEAR-FAULT
GRENADA TROUGH
1000
AVES SWELL
1000
TANNER BASIN
S.D. TROUGH
2500
2500
1000
2000
TOPOGRAPHY DATA LACKING

FIG. 6—NEGATIVE STRIP AND SERPENTINITE INTRUSIONS

At the south end of the Arc it is a little more difficult to make the connection since much of it is covered by water--though the water is of no great depth (500 fathoms). Barbados can be nicely joined to Trinidad geologically and topographically; the submarine-ridges bend around in such a manner as to make the connection.

In the Eocene of both Trinidad and Barbados are found radiolarian beds possibly indicative of deep-sea conditions immediately following a deformation, and there is good evidence of this deformation in the great unconformity below the Scotland beds of Barbados and in the conglomerates which lie above it; and similarly in the unconformity and boulder-beds above it (Mount Moriah Formation) found in Trinidad.

Tobago, which lies to the north of Trinidad, most probably is equivalent to rocks which must now be submerged to the west of Barbados, and it was probably these rocks, and not the crystallines of far-distant South America, which yielded the coarse sandstones and conglomerates of the Middle Eocene Scotland beds.

(2) Gravity-anomalies--The continuation of the strip of strong negative anomalies previously known to exist north of Haiti and Puerto Rico [2, 21] has been traced eastward and then southward, following the trend of the Lesser Antilles and crossing Barbados. As shown in Figure 6, the strip continues over Trinidad and thence westward, probably making an unexpected S-curve to a point north of Bonaire. This explains the +85 value on Curaçao found by Vening Meinesz and the -72 north of Goajira Peninsula. From the latter station the negative strip probably originally extended southwestward along the Cordillera Central.

It appears that the Caribbean Range of eastern Venezuela is not a continuation of the Caribbean Range farther west in the vicinity of Caracas, since the negative strip must cross diagonally the bay which separates the two ranges. Actually these ranges lie on opposite sides of the major syncline. The west-north-west structural axes described by Kamen Kaye [22], which emerge at the coast near Barcelona, actually indicate the major trend. Just as Kugler [4] has indicated that the east-west trend of the North Range of Trinidad is oblique to the major axes of folding which are east-north-east, so is the Caribbean Range of Venezuela oblique to the structural trends there. The west-north-west axes of Bonaire, Curaçao, and Aruba also indicate the trend of the negative strip and hence major structure.

(3) Serpentinite intrusions and the negative strip--Serpentinized peridotite intrusions occur all along the great negative strip of the East Indies, and similarly are present in the West Indies. Apparently they come up along each side of the strip, but only in a few cases are both sides exposed and not covered by younger rocks. They are intruded only during the first great deformation producing the strip. The writer has suggested elsewhere that they are a water-rich product of partial fusion of the peridotite substratum squeezed off as a result of the differential pressures accompanying deformation. Where the upper crust is buckled down into the peridotite substratum, conditions for the formation of this magma and its migration to the surface through the vertical limbs of the down-buckle are fulfilled. Any later deformation shoving the down-buckle again into the peridotite substratum does not produce such intrusions. Apparently the bottom of the down-buckle may become sealed by fusion, or else all of the low-melting constituents of the underlying peridotitic material have been removed during the earlier cycle. The writer's experience with serpentinite intrusions in the field and a search of the world literature indicate that such intrusions occur under no other conditions [22a].

These serpentinite intrusions thus become useful guides in the interpretation of any region such as the West Indies. The serpentinites clearly indicate the former extension of the negative strip from the west end of Haiti along the north coast of Cuba, and thence probably to Guatemala. It seems likely that movement along the Bartlett Trough Fault, probably in Miocene time, permitted Cuba to be released from compression; and thus the down-buckle causing the negative strip has been dissipated by fusion, isostatic uplift, or both, so that now anomalies greater than -50 are rare and the field of negative anomalies has broadened considerably.

It is interesting to note that the serpentinite belt of the Alps has been long known and studied. The anomaly-field there is also a broad but relatively low negative one, so a series of events similar to that in Cuba might be postulated for it.

At the southwest end of the West Indian negative strip, a double belt of serpentinite intrusions is found which follows the Cordillera Central across Colombia into Ecuador. No doubt the negative strip once existed between these two zones of intrusions but has probably now disappeared, as suggested by the high mountains indicative of isostatic uplift.

Serpentinite intrusions are also found in northern Espaniola, central Puerto Rico, northern Venezuela, on the islands of Orchila and Margarita, and at Cape Vela on the Goajira Peninsula. They do not outcrop in the Lesser Antilles but if they were present (and they probably are) there would be no chance to find them since they would be covered by post-Eocene volcanics and sediments. One would expect to find them in the North Range of Venezuela, though none have as yet been reported.

(4) Age of the negative strip--The age of the great deformation can be nicely bracketed in Barbados as previously indicated (end of Middle Eocene). The serpentinites of Cuba are intruded during the deformation, and the deformation involved Lower Eocene beds but not Upper Eocene (based largely on data which Dickerson very kindly placed at the writer's disposal).

Many geologists in the West Indies would no doubt be inclined to consider the late Miocene deformation the great diastrophic epoch in the Area. In the writer's opinion this is not the case. Post-middle Eocene sediments laid down in the trough over the original down-buckle will be particularly susceptible to any later movements on the down-buckle. If after the original down-buckle occurred a further compression takes place, these sediments will be caught in a sort of jaw-crusher between the two sides of the down-buckle. The result will be intense deformation over this relatively narrow but long zone, which is exactly what is found in certain parts of this region. The effects of such superficial deformation will be much more apparent than those of the original major deformation, which may produce relatively slight folding and thrusting at the surface except where the down-buckle crossed basins of deep sedimentation. In the latter case these plastic sediments are liable to be squeezed out of the center of the down-buckle like tooth-paste out of a tube, and may be underridden by the main crust as it forces its way down over "rolling hinges" at either side of the buckle. The experiments which Kuenen [23] has recently conducted indicate what may be expected.

A very similar situation to that described in the paragraph above obtains in the East Indies. Both Umbgrove [24] and Kuenen have considered that the negative strip was formed in Miocene time, based on the narrow zone of intensely deformed Miocene and older rocks on islands located on the negative strip. The serpentinite intrusions are, however, latest Cretaceous or early Eocene in age, and so probably is the formation of the negative strip. The intense local Miocene deformation is merely the "jaw-crusher" effect accompanying a lesser deformation at that time.

How such a down-buckle can be maintained for so many millions of years without disappearing remains an unsolved question. Though Vening Meinesz and other geophysicists are loath to accept this conclusion, it seems inevitable to the geologist. Judging from the relations in Cuba, it seems likely that a certain amount of compression must be maintained in the crust for the down-buckle to persist. Where this is removed, the down-buckle spreads, rises, and disappears.

(5) Submerged canyons and basins--A great canyon over 2500 fathoms deep is present at the eastern end of Anegada Passage (Fig. 5) and another canyon probably drains from the west end of the Passage into the Caribbean. Like many other such canyons on continental slopes, the eastern one resembles a great submerged river-channel in all respects. This canyon is much too deep to fit Shepard's [25] glacial lowering of sea-level hypothesis, and little mud would be available during the 100-meter Pleistocene lowering of sea-level to accommodate Daly's [26] "density-current" hypothesis, since the ocean waves would in this case merely be beating on coral reefs and solid rock instead of a muddy shelf. The hypothesis of change in ellipticity of sea-level which MacClintock and the present writer [27] advanced might be applicable to this valley. In fact, the hypothesis predicted that a valley at latitude 19° would be about 2900 fathoms deep, which probably is close to the actual depth. The writer, however, has no great faith in this hypothesis other than that it is an interesting possibility to be kept in mind when critically examining submarine-topography.

A number of basins or troughs were found in the Caribbean which apparently have extremely level floors (see Fig. 2). The ridges separating these basins have a rather rough, probably gullied, surface. In the Grenada Trough, in which more soundings were obtained than in the others, a marked flat at 1670 fathoms was found on the southern traverse and at 1617 fathoms on the northern traverse. This might indicate a southward slope of 60 fathoms between the two traverses.

The flatness of the bottoms suggest sedimentary fill of possible lake-basins under conditions of lower relative sea-level. The only outlet of the Grenada Trough lies at the southwest end. Here a rather broad smoothly curving valley was found which has a maximum depth of 1235 (?) fathoms and connects the Trough with the Tanner Basin. The Tanner Basin has a depth of nearly 2700 fathoms, and the valley connecting the two shows up clearly in contours of Figure 1.

The fact that the lowest outlet of the Grenada Trough is at 1235 fathoms and the bottom of the Trough greater than 1600 fathoms would necessitate some 400 fathoms of lowering by evaporation if the lake-hypothesis were correct. From the thermal gradient of the water in the Caribbean, it appears that the lowest outlet lies in the neighborhood of 650 fathoms, so that if all of the basins are to be interpreted as lakes, the main part of the Caribbean would have had to evaporate from 650 fathoms down below 2500 fathoms. Whether such evaporation is possible in a limited interval, the writer has not yet had time to investigate.

In order to arrive at a satisfactory explanation of these flat-bottomed basins, considerably more sounding data are necessary. The extent of the flat areas, their shape, possible terraces along the sides of the basins, and certain unfilled deeps need to be investigated.

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CRYSTAL-CHRONOMETER TIME IN GRAVITY-SURVEYS

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The United States Coast and Geodetic Survey each year measures the value of gravity at a few selected stations in the United States. These stations are generally rather widely spaced so that the most satisfactory instrument for this work has been some form of pendulum-apparatus. The measurements are made by determining the period of the pendulum at the base-station at Washington, and then at the field-stations and again checking in at the base-station after a few months' work. The accuracy desired in this work is one part in a million.

The most important factor in determining the period of the pendulum is the time-interval of the swing. This interval in early gravity-work was determined from chronometers, whose rate was obtained first by astronomical time-sights, then by telegraphic time-signals, and finally by radio time-signals. The errors in time by these methods were of such size that it was necessary to swing the pendulums at least twelve hours to obtain the accuracy desired. During the last decade, short-wave radio time-signals have been broadcast by the Naval Observatory through the Naval Communication Service about every two hours so that it has been possible to time the pendulums directly from these signals without the use of chronometers. This method improved the accuracy of the time-interval so that the period of swing could be shortened to six hours. The time-signals are broadcast with an accuracy such that a much shorter interval of swing should be possible, but there are many small errors that creep into the reception and recording of these signals when the field-party is at a considerable distance from Washington.

Some of the errors are no doubt variable lags in the radio and amplifying circuits of the field-stations, and some are believed to be variations in actual travel-time of the signal from Washington to the field-station. There is considerable evidence in support of the belief that sometimes the signal recorded has actually traveled around the Earth by the longer path rather than by the more direct line. Signals broadcast on different wave-lengths will generally have different travel-times and those on the same wave-length will vary depending upon whether the travel is during daylight or darkness. It is thus evident that radio time is not entirely satisfactory for accurate gravity-work until more information is available on these lags. In local projects where the base-station and the field-stations are not more than 100 miles apart, some very accurate measurements have been made by swinging pendulums at both stations simultaneously, and using some arbitrary radio signal as the timing point for both pendulum-instruments. This method practically eliminates time from the computations and compares the pendulums directly with each other. Where the stations are 1000 miles or more apart, the radio lags again enter into the problem.

When the United States Navy-American Geophysical Union Gravity-at-Sea Expedition was being organized, the question of more accurate time came up and Dr. Richard M. Field, Chairman of the Union's Special Committee on Geophysical and Geological Study of Oceanic Basins, and Dr. Maurice Ewing, chief scientist of the Expedition, were instrumental in securing the cooperation of the Bell Telephone Laboratories of New York, who consented to design and construct a portable crystal chronometer and loan it to the Union for this Expedition. Dr. Ewing's paper contains a report of that Expedition so that it will not be necessary in this paper to touch upon the details of the Expedition.

The chronometer was built in accordance with the latest designs of the Bell Telephone Laboratories and proved to be a wonderfully accurate timepiece. The rate of the chronometer was so small that it could be neglected in most of the gravity-computations, even though these observations extended over a period of but half an hour.

The Vening Meinesz gravity-instrument makes use of a photographic method of recording the movements of the pendulums. It was therefore quite easy to have the synchronous motor, which was driven from the output of the crystal chronometer, mounted directly on the instrument so that it interrupted the light-source every half-second without the use of relays or electrical devices. This eliminated all possibility of variable lags in mechanical or electrical circuits.

The crystal chronometer was started on November 29, 1936, and ran without interruption until January 14, 1937, when the Expedition terminated at Philadelphia. The first part of the cruise was in tropical waters and the last part in mid-winter temperatures of the Atlantic Coast. The instrument was therefore subjected to a very wide temperature-range. During the 46 days of operation the chronometer gained 0.36 second, or an average daily rate of 0.008 second. This rate was not entirely constant but varied somewhat with the temperature-changes. The Bell Telephone Laboratories have just installed a new and improved crystal in the chronometer which they feel sure will show a much smaller effect of temperature-changes. The improved chronometer will be given another field-trial in the near future and it is hoped that the rate will be even better than the previous one.

The rate of the chronometer during the Expedition was determined from radio time-signals. Of course, the same errors of lags in circuits and travel-time are apparent in these signals, but these variations, which are very serious for a swing of an hour or so, assume much less importance when the time-interval is extended to several days. Enough time-signals were recorded each day so that the mean of all observations gave a very good rate for the chronometer.

The crystal chronometer certainly measures time with an accuracy never before obtained outside of the large time-laboratories of the country, and from the tests so far made the chronometer is rugged enough so that it may be transported from place to place without seriously disturbing its rate. It would therefore appear that this instrument furnishes the means of measuring gravity at widely separated stations with an accuracy greater than that now obtained and in a much shorter period of time. This is the goal which we are always aiming at--greater accuracy at smaller unit cost.

The chronometer should also be very useful in astronomical observations, where time is always an important element. The rate is so constant that time-sights for longitude-observations could be made at any time when the stars were visible without waiting for the radio time-signals. At the present time, these star-sights must be made very near the time of a radio time-signal broadcast if accurate work is to be secured. There are also a few longitude-observations in the United States that stand out from others in the same network for reasons unknown unless the errors are due to time-signal reception. Repeat-observations at these stations have generally checked the original observations. As stated earlier in this report, there is considerable evidence to support the theory that the signal actually recorded has sometimes traveled around the Earth by the longer path. It would be most interesting to reobserve some of these stations using the crystal chronometer as a timepiece.

During the last world-longitude work, when the United States Coast and Geodetic Survey made longitude-observations in the Hawaiian Islands, it was necessary to carry the time for these observations by use of the gravity-pendulums. A crystal chronometer such as that now available would certainly have added much to the accuracy of the work and have saved much labor and computations.

There is hardly time at this meeting to go into any of the details of construction or operation of the chronometer. But I believe it appropriate to state that the power required to run the clock is so low that it may easily be obtained from storage-batteries and the ordinary heavy-duty B-batteries in common use. The A-current required is 2.5 amperes at 10 volts and the B-current is 50 milliamperes at 135 volts. Either voltage may be varied by as much as ten per cent without seriously changing the rate of the chronometer.

I have no doubt but that the portable crystal chronometer will become a very useful tool in scientific research and observations wherever accurate time or uniform movement is required.

U. S. Coast and Geodetic Survey,
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RECENT GRAVITY-WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY

Carl I. Aslakson

The purpose of this paper is to give a brief summary of the gravity-work of the United States Coast and Geodetic Survey since August 1936 and to present briefly some of the recent developments in field-methods.

The following gravity-projects have been completed during this time: Fifteen new stations and one reoccupation in Virginia; 21 new stations and 19 reoccupations in Mississippi, Louisiana, Oklahoma, and Texas; 20 new stations and one reoccupation in southwest Alabama. The gravity-party is still in the field observing in the Southwestern States.

It may be of interest to learn that the United States Coast and Geodetic Survey is now marking or referencing gravity-stations with a standard gravity-disc usually set in a concrete post. Furthermore, all recent gravity-stations are easily accessible. The party now in the field is using a house-trailer with much of the apparatus such as the radio, chronograph, amplifiers, chronometer, and batteries, permanently installed in it. This necessitates the selection of a station-site which should be readily available for future reoccupation.

The principal innovation in recent gravity-work consists in the use of two sets of Brown apparatus to obtain two simultaneous determinations of gravity at each station. The advantages of this procedure are readily apparent. An indication of the accuracy of any observation at a station is given by the difference in period between the two pendulums which should be practically constant. Since the time-signal corrections affect both pendulum-computations by a like amount, this difference is independent of these corrections. When a single pendulum is swung for a 6-hour interval, an intermediate time-signal is observed in addition to the signals at the beginning and end of the 6-hour interval. The only indication of the accuracy of such observations is derived from computing the period from each of the three time-epochs. When the signals have large corrections, these periods will differ by correspondingly large amounts. Since the field-party has no knowledge of the direction or amount of signal-corrections, it is necessary to make a second observation at the station when only one pendulum is observed and when signal-corrections are large. When two pendulums are used simultaneously, the period-difference between them should remain constant within limits for each of the time-epochs from which the period is computed, and when both pendulums show corresponding variations a signal-correction is indicated.

An examination of the variation of the period-differences between the two pendulums provides some interesting figures: For a total of 79 observations, 52 per cent of them fell within the limits of ± 1 in the seventh decimal place from the mean difference in period, 70 per cent fell within ± 2, 86 per cent within ± 3, and 92 per cent within ± 4. Only 8 per cent of the observations showed a period-difference which fell outside the limits of ± 4 in the seventh decimal place from the mean period-difference. Those which fell outside varied from ± 5 to ± 9 and were reobserved. The period-difference of each reobservation was within the limits of ± 4.

These pendulums have not as yet been restandardized at Washington but, from an analysis of the pendulum-period differences, indications are that, when two pendulums are used and reobservations are made when the period-difference is large, the observations will have a probable error of less than one milligal.

Probably the most interesting feature of the past season's work was the large number of reoccupations of old gravity-stations in the southwest. These reoccupations include the work of seven different observers who established stations in the years 1895, 1909, 1910, 1911, 1914, 1922, and 1933. The results obtained were gratifying. When the original station could be exactly recovered and when the results are considered with regard to sign, the average difference between the values of gravity obtained in the previous and present surveys is about one milligal for the work of five of these observers. There is a maximum difference of three milligals between present and previous work for these same observers.

The observations at a few of the stations of 1922 did not compare satisfactorily with the previous survey and it is planned to reoccupy the remaining stations of one season's work with the two sets of Brown apparatus as rapidly as economic routing of the field gravity-party permits.

Indications are that a portion of the gravity-work completed in 1933 is consistent with itself but should be corrected by a constant amount at certain stations. The present field-party is reoccupying more of the stations of 1933 in order to be able to establish the size of these corrections.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GEODETIC WORK EXECUTED IN THE REPUBLIC OF MEXICO IN 1936

Manuel Medina

During the year of 1936, the Geographic Branch of the Department of Geography, Meteorology, and Hydrology continued the normal progress of geodetic and geographic operations in accordance with the Government's program for that year. The geodetic operations consisted of (1) reconnaissance for first-order and second-order triangulation, (2) azimuth-observations and zenith-observations at the vertices, (3) continuation of the Mexico-Acapulco precise leveling, and (4) determination of the intensity of gravity. The geographic work consisted of (1) reconnaissance and observation of topographic triangulation, (2) traverse-loops on various roads and highways of the country for the improvement of the geographic maps.

Triangulation-reconnaissance

Proceeding from the geodetic chain which crosses the State of Zacatecas, two chains of triangles were planned eastward and westward, respectively, in order to cover some regions of the said State where it is necessary to establish control-points to support the topographic surveys. The proposed figures are two central-point pentagons and a quadrilateral, the sides of which have an average length of 30 km. The regions, which these figures will cover, have large, important agricultural and mining surveys of private properties which can be used in the formation of topographic network if the necessary geodetic control-points are established.

Geodetic triangulation

Lerma River--Five quadrilaterals were established. The average triangle-closure of this chain was 2″.83. The average probable error of a direction repeated 12 times at the different vertices was 0″.55. The average linear-closure was 62 units in the 7th decimal place of the logarithms. The average of the mean error of an observation after the adjustment was 1″.35.

Jalisco--Two quadrilaterals and one central-point figure were established. The average triangle-closure was 3″.10. The average probable error of a direction repeated 12 times was 0″.47. The average linear-closure was 275 units in the 7th decimal place of the logarithms. The average mean error of an observation after the adjustment was 1″.87.

Guadalajara (Jalisco) Geodetic Base--Length of the base, 8009.731 meters; probable error, 1.00 mm; accuracy, 1:8,000,000.

Mexico-Acapulco precise leveling--The work accomplished during the year 1936 consisted of the leveling of 16 links with a total of 68 sections; nine sections, or 14 per cent of the approximate total, having been rerun. This leveling amounted to 78 km.

Gravity-measurements

By the initiative and under the auspices of the Pan-American Institute of Geography and History a circuit of gravity and magnetic measurements was made in Central America during May to August 1936. The instruments used were the following: Mendenhall type gravity-apparatus with three pendulums of invar steel constructed by the Gaertner Scientific Corporation, Chicago, United States of America; two standard sidereal chronometers; one hack-chronometer; one vernier-chronometer; one short-wave, radiotelegraph receiver with its accessories; and one Chasselon theodolite-magnetometer with additional inclination-needle.

The gravimetric and magnetic observations were made in the following places:

City of Guatemala, Guatemala--Observations were made in the building occupied by the Guatemala National Observatory, the pendulum-receiver being installed directly on the mosaic floor. The plane of the pendulum-oscillation was approximately north and south. The magnetic observations were made at the Aurora Military and Civil Airport, with a traverse-tie between the magnetic and the gravimetric stations.

Puerto Barrios, Guatemala--Only magnetic observations were made, because no suitable place for the gravity-observations was found.

City of San Salvador, El Salvador--The gravity-observations were made in the building of the Seismological Observatory; the plane of the pendulum-oscillations was oriented approximately from east to west, the pendulum-receiver having been mounted on the cement floor. Near the Observatory, close by the powder-magazine, an athletic field is located where some magnetic observations were made which it was not possible to complete because of a heavy storm which then raged in that region.

La Union, Port on the Gulf of Fonseca, El Salvador--The place of observation was established in a room on the ground-floor of the Hotel America facing Central Park, the plane of pendulum-oscillation being oriented from east to west.

City of Tegucigalpa, Honduras--The gravity-station was established in the National Theater, at the foot of the stage on a mosaic floor. The plane of pendulum-oscillation was oriented from east to west. Magnetic determinations were made at the Toncontin Airport, 6 km from the City, where an astronomical north-and-south line was marked on the ground so that the pilots could correct their airplane-compasses.

Port of Amapala, Honduras--Magnetic observations were made near the landing field, about 2 km from the port and near the shore.

City of Managua, Nicaragua--The gravity-apparatus was installed in the building of the Mexican Legation in Nicaragua, in a large room with a mosaic floor, the plane of pendulum oscillations being oriented approximately from east to west. The magnetic observations were made in Mars field, situated south of the City, near the Presidential house.

Results of the gravity-observations

Station	Gals	Probable error
Guatemala, Guatemala	977.973	±0.0029
San Salvador, el Salvador	978.185	±0.0009
La Union, el Salvador	978.330	±0.0014
Tegucigalpa, Honduras	978.102	±0.0020
Managua, Nicaragua	978.278	±0.0009

As soon as some topographic maps are obtained of the occupied zones, the calculation of the corrections for topography and isostatic compensation will proceed.

Results of magnetic observations (reduced to International Magnetic Standards)

Station	Coordinates		Date	Declination, E	Inclination, N	Horizontal intensity
	Lat. N	Long. W				
	° '	° '	1936	° '	° '	γ
Guatemala, Guatemala	14 38	90 30	May 25-28	7 41.8	42 29.7	31363
Puerto Barrios, Guatemala	15 44	88 35	June 2- 3	7 19.3	45 16.5	30772
La Union, el Salvador	13 20	87 51	June 22-24	7 18.0	41 11.3	30833
San Salvador, el Salvador	13 42	89 11	June 12-17	......	42 07.7	30403
Amapala, Honduras	13 18	87 39	July 12	7 18.0	41 30.7	30836
Tegucigalpa, Honduras	14 06	87 13	July 4- 6	7 13.0	43 06.0	31084
Managua, Nicaragua	12 10	86 16	July 19-22	7 50.0	41 26.8	31298

Reconnaissance and observations of topographic triangulation

In the State of Jalisco a reconnaissance of triangulation of topographic character was made, which extends from the Guadalajara Base northward to connect with the Juchipila Canyon Topographic Chain, in the State of Zacatecas. The Jalisco Project is formed by five quadrilaterals the sides of which have an average length of 25 km.

The Juchipila Canyon Triangulation (State of Zacatecas) is formed by 14 quadrilaterals, of which six were observed during the year. These observations were made with a repeating Wild theodolite on which the angular readings can be estimated to 0!1. The mean error of triangle-closure was 16 seconds. The mean linear-closure of the quadrilaterals was 528 units of the 7th decimal place of the logarithms.

Traverse-loops

These surveys are being made in the States of Zacatecas and Jalisco using theodolites of one-minute angular approximation and using the metric tape or the stadia to measure the distances. Every five km, azimuth control-points were established, using solar observations.

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GEODETIC CONTROL ALONG CENTRAL AMERICAN BOUNDARIES

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In presenting this paper before the American Geophysical Union, the writer feels that he should inform the members that it will not be a technical discussion of geodetic problems, but rather a general description of the geodetic and mapping operations that are being carried out, under his direction, along the boundaries between the Republic of Guatemala and the two adjoining Republics of Honduras and El Salvador.

The writer believes that the geodetic part of this work should be of special interest to the Union. The seven countries properly considered in the Central American Zone (Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, Panama, and British Honduras) have thus far made very little progress in detailed mapping or in accurate geodetic surveys. The geodetic work now in progress is not a local affair of a single government but is international in character, and the engineers of the three Republics concerned are taking considerable interest in its progress.

It is more than probable that in the near future at least two of these countries will establish geodetic and mapping sections in their engineering departments with the object of making extensive internal surveys. These countries realize that the full development of their natural resources will only proceed as accurate map-knowledge of the regions is obtained.

Additional interest should be aroused in the probable extension of the present first-order triangulation-arc southward along other Central American boundaries. A number of these boundaries south of the present work have yet to be surveyed and monumented. It is hoped that in the not too distant future a complete net of first-order triangulation will be established from Guatemala south to Panama and Colombia. The establishment of such a net of precise control along these boundaries should afford adequate basic control for any mapping work that may be contemplated in the future.

Then, too, there is a possibility of extending the present precise arc northward, across Guatemala and into Mexico, to connect with the first-order arc along the 98th meridian in the latter country. The positions in the 98th meridian arc are based on the North American datum, and this connection would provide a single datum for all geographic positions from the Canal Zone northward into Canada.

A commission of British engineers has recently been engaged in surveying the southern part of the boundary between Guatemala and British Honduras. This commission established an arc of triangulation in southern British Honduras in order to determine the 80-mile tangent that forms this section of the boundary. Although the work of this commission has not yet been accepted by the Guatemalan Government for various political and historical reasons, nevertheless it is understood that the accuracy of their geodetic work is of a high order.

It will not be difficult to tie the present precise arc to this system, but an advance of the control-net in this direction will not help in the problem of connecting to the 98th-meridian arc, as the northeastern part of Guatemala and the southern part of the State of Yucatan are very difficult areas for triangulation. Most of this area is rather flat and is covered with a dense jungle. Triangulation could only be extended with the construction of high towers, and the costs would be prohibitive.

The best way of extending the present arc northward is through the western highlands of Guatemala, where many mountain peaks are available and where it would not be difficult to lay out well-constructed figures. The writer has no personal knowledge of the topography of southern Mexico but believes that it is somewhat similar to that of western Guatemala. It should not be difficult to extend the 98th-meridian arc southward along the west coast of Mexico to the Guatemalan border.

The boundary between Guatemala and Mexico was surveyed and monumented in 1883 to 1896. The geographic positions of the boundary-monuments were established by individual astronomic observations, and these monuments were not connected by triangulation or accurate traverse-lines. It seems improbable that this boundary will be entirely resurveyed in the near future to obtain greater accuracy in the positions of boundary-monuments but, with the extension of precise control northward to the Mexican border, it is probable that certain of the monuments in the western section will be tied to the control-net.

The writer is unable to judge whether it would be more desirable to set up an independent datum for Central America, or whether at some future time, when proper connections have been made to the 98th-meridian arc, it would not be more advisable to base all geographic positions in these countries on the North American datum. This will be a problem which should be of definite interest to the Union.

The writer has been engaged since 1933 in surveying and monumenting the boundary between Guatemala and Honduras. This boundary extends from the Caribbean coast 260 km inland, in a southwesterly direction, to the northwest corner of the Republic of El Salvador.

The field-engineering work on this line was completed in June 1936 and included the construction of more than 1000 concrete monuments of various types and sizes; the cutting of a vista from 20 to 30 meters wide along a major portion of the line; and the preparing of 17 maps of the frontier-zone.

It was necessary to establish a system of triangulation along the entire boundary to provide a unified net of control for the geographic positions of the boundary monuments and for the various mapping operations. It was decided that the system should be of first-order accuracy, primarily because of the importance of determining accurate geographic positions for the principal monuments along an international boundary, and secondarily, for the purpose of helping these two governments in the solution of their future geodetic problems.

It was believed that if a first-order arc of triangulation were available and if a few local engineers were trained in this class of work, these governments would see the advisability of extending the system into their own countries for the control of property-surveys and for general mapping work. Probably this will be done in the future, although perhaps rather slowly at first until such a time as the true value of precise control is appreciated. Hopeful signs of such future work are to be found in the recent purchase of first-order observing equipment by the governments of Guatemala and El Salvador. These two countries have only recently started the surveying and monumenting of their common boundary, and the instruments mentioned were purchased in duplicate, so that at the termination of the demarcation, each government will have a complete set for internal surveys.

In December 1933 the Guatemala-Honduras Demarcation Commission started the reconnaissance-work on the triangulation-system. It soon was apparent that the work would be very difficult, not only in locating the stations but also in the actual observing work. It therefore seemed advisable to accept a previous offer of the United States Coast and Geodetic Survey to cooperate in the highly specialized work of observing. Such cooperation would not only save the time that would be required for the Commission's engineers to gain experience in precise observing methods, but would also save excessive costs in the purchase of special observing and astronomic instruments.

Arrangements were made in which the United States Coast and Geodetic Survey agreed to detail two expert engineers for the observing and to lend to the Commission the necessary instrumental equipment for this work. In turn, the Commission agreed to pay all costs of transportation of men and instruments and to pay salaries or bonuses to the engineers, together with their living and field expenses while in these countries. Lieut. J. P. Lushene was placed in charge of the work, and he arrived in Guatemala in December 1934 with the equipment for two observing parties and other special equipment for the astronomical work. Philip Welker, a temporary employee of the same organization, arrived early in January 1935.

Previous to the arrival of these engineers, the Commission's engineers had spent more than a year on the reconnaissance and signal-building work. The difficulties encountered in this work were tremendous. Over half the country traversed by the boundary is a rough, heavily timbered jungle, ranging in elevation from sea-level to 8000 feet. There are very few trails through this section of the frontier-zone, and large areas are practically uninhabited. Problems of transportation and food were very difficult, especially during the rainy seasons. The work was carried on without regard for the changing seasons, as every effort was being made to complete the reconnaissance-work before the arrival of the engineers of the United States Coast and Geodetic Survey.

The system, as finally located, is made up of 32 first-order and 28 secondary intersected stations. Of the secondary stations 23 were located on or very close to the actual boundary-line and at varying intervals along this line for the purpose of controlling the transit-traverse work. Thirteen quadrilaterals were required to connect the two base-lines, which had been placed at the opposite ends of the system. The axial distance through the system is 180 km and the strength of figures, as computed from the reconnaissance-data, gave the $\sum R_1$ value as 99.

It was found during observing that two diagonals, each in different quadrilaterals, were not intervisible. However, even with this decrease in the strength of figures, the value of the $\sum R_1$ values was only increased to 104.

Two parties were organized and the angle-observing was started at the south base-line stations on January 20. Lieut. Lushene was in direct charge of the work and also acted as the observer in the first party, while Mr. Welker was the observer in the second party. A number of the local engineers accompanied both parties in order to gain experience in this class of work. The two parties worked on opposite sides of the quadrilaterals and were always in close contact with each other by means of night-signaling with lamps.

All first-order observations were made at night in conformity with the standard practices of the United States Coast and Geodetic Survey. Reciprocal vertical angles were observed, partly during the day and partly at night on the station-lamps with very satisfactory results. Daylight-observations were made for the secondary work on the intersected stations.

The light-keepers were selected from the personnel of the Commission. Most of these men had had previous experience as rodmen or chainmen, although a few were entirely inexperienced in engineering work. These light-keepers were given a week or more of training in sending and receiving code-signals with their lamps and, although some doubt had existed as to their ability to carry on the work, it was found that they made very satisfactory light-keepers.

The angle-observing was completed on about June 15, an average of ten days per station per party. Conditions of weather were very unsatisfactory during most of this period, and observing records show that a number of stations required 15 or more days to complete.

Experience has now indicated that the most favorable weather for observing is from December to March. The dry season extends from late November to early June. However, during March the air becomes very smoky, owing to the custom of clearing new lands for planting during the last of the rainy season and then burning the refuse in March after it has thoroughly dried out. Long-distance observing is very difficult during April and May because of this smoke, which usually continues until the first rains in June. Once the rainy season has fully set in, usually by the middle or last of June, cloud-conditions in the higher mountains seriously interfere with observing. Then, too, the mountain trails become practically impassable, and field-work must be given up.

As soon as the observing had been completed, Mr. Welker returned to the main office of the Commission in Guatemala City, where he was placed in charge of the computing and least-squares adjustment-work.

Two astronomical stations were established, one at each of the base-lines, where first-order observations for latitude, longitude, and azimuth were made by Lieut. Lushene. The results of these observations, as indicated by the probable errors in positions and azimuths, were excellent.

The northerly base-line was located and measured in 1933 by the engineers of the Commission. Invar tapes and other equipment of the standards adopted by the United States Coast and Geodetic Survey were used. However, the base-measuring crew was inexperienced in this class of work and, although every effort was made to conform to the specifications of the Survey for first-order measurements, the probable error of the work gave an accuracy of only 1:638,660.

The remeasurement of this base was delayed on the advice of officials of the United States Coast and Geodetic Survey, who considered it advisable to wait until the length-closures between the two bases had been computed. This length-closure was found to be 1:101,000, and it was therefore deemed unnecessary to make the remeasurement, as the accuracy of the length-closure was much greater than the first-order requirements of 1:25,000.

The southern base-line was measured in 1935 under the direct supervision of Lieut. Lushene. The probable error of this measurement was found to be 1:1,502,000, which is well within the first-order limits of 1:1,000,000.

At the conclusion of the astronomic work, Lieut. Lushene returned to Washington, while Mr. Welker was retained by the Commission as its chief computer. During October, Mr. Welker was taken suddenly ill with a serious throat infection. As he did not respond satisfactorily to medical treatment in Guatemala City, he was first sent to the United Fruit Company's hospital at Quirigua, Guatemala, and later was taken to New Orleans. It was with great sorrow that we learned of his death on December 16. One and all, the members of the Commission, who had lived and worked with Mr. Welker, had the highest regard for his ability and for his friendly personality.

Because of Mr. Welker's illness it was found necessary to ask the United States Coast and Geodetic Survey to complete the least-square adjustment of the system. These adjustments were completed in Washington by three computers of this organization, working on extra time and under the direction of Mr. H. G. Avers.

The character and accuracy of the work is indicated by the following data:

Average closure error of 48 triangles without regard to signs	$0''.90$
Maximum error of closure in any triangle	$2''.63$
Mean error of any angle	$\pm 0''.64$
Probable error of an observed direction	$\pm 0''.51$
Error in length between bases:	
Before satisfying angle- and side-equations	1:87,560
After satisfying those equations	1:101,328
Discrepancy in azimuth between Laplace stations	$3''.86$
Southern astronomic station:	
Probable error in latitude	$\pm 0''.07$
Probable error in longitude	$\pm 0^{s}.003$
Probable error in azimuth-determination	$\pm 0''.28$
Northern astronomic station:	
Probable error in latitude	$\pm 0''.06$
Probable error in longitude	$\pm 0^{s}.005$
Probable error in azimuth-determination	$\pm 0''.24$

The position-closure between the two astronomic stations, as computed through the system, was $12''.9$ in latitude and $11''.4$ in longitude. Because of the high precision of the connecting system of triangulation, it can be assumed that the major portion of these position-closures was due to the inclination of the verticals at the two astronomic stations. Corrections to these verticals could not be calculated, as there were no topographic maps available for computing the effect of adjacent masses on the plumb-line.

An equation for the azimuth-closure between Laplace stations was included in the least-squares adjustment of the system, but the latitude- and longitude-equations were omitted. A provisional datum was established at the southern astronomic station, whose position was adjusted for one-half the above noted closure-errors in latitude and longitude [(A - G)/2]. This provisional datum, which has been named the Ocotepeque Datum, will undoubtedly be readjusted as more data become available from new astronomic positions.

A brief description of the transit-traverse and map-work of the Commission may be of interest to the members of the Union. While the triangulation-work was progressing, four other engineering parties were engaged in surveying the actual boundary-line. In order that both governments should be equally represented in the location of the actual line, an engineer from each country was assigned to every field-party engaged in this class of work. Each of these two engineers was required to repeat all distance- and angle-measurements and to maintain separate record-books of his measurements. The individual measurements of these engineers were required to agree within certain limits, otherwise the measurements in question were to be repeated by both men.

A transit-stadia traverse was run along the entire line, as the majority of the country was too rough to permit accurate chaining without excessive costs. New Keuffel and Esser 30-second transits with control-bubbles attached to the vertical circles were provided for this work, and circular bubbles were attached to the stadia-rods to aid in plumbing these rods on steep slopes.

The straight-line sections of the boundary were projected by double-centering the forward point. In the meander-sections of the boundary, double deflection-angles were measured at all station-points. Foresight and backsight stadia-distances were read from each station, and vertical angles to a definite point on the rod were recorded. If the distance between stations was over 300 meters, intermediate set-ups were made, as the maximum length of stadia-shots was limited to 300 meters. Solar observations for azimuth were taken at frequent intervals.

The stadia-traverse was adjusted in sections, each section beginning and ending at one of the secondary triangulation-stations which had been established at varying intervals along or very close to the line. These traverse-adjustments were made in the usual manner, the closure-errors in latitude and longitude being divided by the total line-distance of the section to obtain factors representing the correction in seconds per meter of distance for latitude and for longitude. The positions of the individual stations were adjusted with reference to the length of the preceding traverse-course, and geographic coordinates were computed to hundredths of a second.

Twenty-five sections of the traverse were adjusted in this manner, and the average degree of accuracy obtained in stadia-work over such rugged country is especially noteworthy. The largest closure-error encountered in any section was 1:133, while the best closure made was 1:6,348. Only two sections showed closures below 1:200, and the arithmetical mean of the 25 section-closures was approximately 1:400.

If the traverse were to be considered as a whole, and if the closures of latitude and of longitude in the different sections were summed algebraically, the distance-closure in the total length of the line (260 km) would be approximately 1:740, which should be considered excellent results for stadia-work in such rough country.

Geographic positions of third-order accuracy have been determined for the boundary-monuments at the 23 secondary triangulation-stations. Two other boundary-monuments were first-order triangulation-stations. The remainder of the monuments, whose geographic positions were computed from the adjusted traverse-line, must be considered as fourth-order positions.

It would have been physically and economically impossible to locate all the boundary-monuments with third-order accuracy, owing to the character of the terrain. To have increased the number of third-order points along the boundary would have required adding a secondary net of triangulation to the primary control and would have resulted in a very decided increase in the cost of this control. It would also have been necessary for the observing parties to spend an additional season on the work, as the main scheme was barely finished before the rainy season set in. The instructions issued to the observing parties at the beginning of the work were that all observing on the main-scheme stations must be completed in one season, and every possible credit is due Lieut. Lushene and Mr. Welker for their excellent work.

The field-conditions encountered in the tropics on this class of control-work are certainly many times more arduous than most working conditions in the States. Similar conditions, involving such hardships as short observing seasons, uncertain weather-conditions, and the lack of roads and trails probably exist only in northern countries like Alaska.

All field-engineering work and the construction of boundary-monuments were completed in June 1936--a period of three years and two months. However, it should be remembered that field-work was not carried on during the worst of the rainy seasons, from July to October, and therefore the total time required to complete field-work was approximately 28 months.

The drafting work was carried on until September 1936, when the final maps were shipped to the Williams-Heintz Company of Washington, D. C., for reproduction by lithography.

The maps were compiled from the 4-lens aerial photographs taken by the United States Army Air Corps in 1932. The basic control was obtained from the triangulation and traverse-work of the Commission, and the topographic data was assembled by the usual radial-line plotting methods that are employed by most United States Government organizations.

These maps were prepared as "planimetric maps," showing roads, trails, settlements, drainage, prominent mountain peaks, principal water-divides, and monument-locations. Thirteen maps were drawn on a scale of 1:25,000, covering the actual frontier-zone to an average distance of five km on each side of the boundary. Two general maps were prepared on a scale of 1:100,000, covering all the area available from the aerial photographs. Two index-maps were drawn on a scale of 1:200,000, one showing the layout of the larger-scale maps and the other showing the triangulation-system.

The maps were drafted on white Duco-painted aluminum sheets, in order to preserve the accuracy of the projections for reproduction in color. The Commission first experimented with drawing paper mounted on aluminum sheets, but found that the paper buckled under local weather-conditions. The white Duco-covered sheets were prepared by the United States Geological Survey and were found very satisfactory, with the exception that the inks smeared rather easily and considerable care had to be taken in the drafting work. As soon as the drafting was completed on a sheet, it was sprayed with clear varnish or artist's fixative, which adequately prevented any further smearing of the work.

All map-lettering, including titles, was set up in type on specially treated tissue-paper and "floated" in position on the varnished surface of the sheets.

The Commission has been engaged since last October in preparing the data for its final report, which should be ready for publication during the latter part of 1937.

A new Commission was organized in February 1936 for the demarcation of the boundary between the Republics of Guatemala and El Salvador. This Commission is made up of three members, one appointed by each of the two countries and a third neutral member. The two governments agreed that the President of the Pan-American Union should select this third member, and the writer was nominated for the position and accepted by the two governments.

The arbitration of the territorial difference will be by direct negotiations between the foreign ministers of the two governments. The work of the Commission is to prepare maps of the frontier-zone, showing the existing status of private property and other important topographic information, and, at a later date, to survey and build boundary-monuments along the accepted boundary-line.

The work of the Commission is divided into two distinct phases:

(1) The preparation of the preliminary maps, which are to show all roads, trails, settlements, drainage-systems, important mountain peaks, and other prominent topographic features. In addition, they will show the existing private property-lines to a distance of one to two km on each side of the approximate frontier. These maps will be used in the arbitration of the territorial claims, and the definite boundary-line will be selected and described from these maps.

(2) The Commission will then survey the boundary-line, using the official description and the maps to identify the controlling points. They will also build a sufficient number of monuments along the line to identify this line properly on the ground. The preliminary maps will be revised and adjusted to accurate basic control and, when published, will show the positions of all boundary-monuments.

The length of the boundary-line between these two countries is approximately 130 km. Through most of this distance the boundary is already fairly well defined and recognized by both governments. There are, however, some sections where territorial claims are conflicting, and it is the earnest desire of both governments in these present negotiations to bring about an immediate and just settlement of their differences.

In January 1935, prior to the actual organization of the new Commission, an aerial photographic survey was made of the frontier-zone by the United States Army Air Corps. The photographic work was done by Maj. W. R. Taylor, pilot, and Sgt. G. W. Edwards, photographer, of the 12th Photo Section of France Field, Canal Zone. A Bagley 4-lens type T-2 aerial camera was used, and approximately 900 vertical photographs were taken from an average altitude of 13,000 feet above sea-level. The area photographed averaged approximately 20 km wide by 120 km long and connects with the photographic work done by the same organization along the Honduran boundary in 1932.

Field-operations on the first phase of the Commission's work were started in March 1936. Two field-parties were organized at that time for the purpose of obtaining the data required for the preliminary maps. Each party was made up of two engineers, one from each country, in order that both governments would be equally represented in the work of identifying the position of private property-lines in the frontier-zone. Contact-prints of the aerial photographs were given to these engineers, and they were instructed to locate on these prints all important property-monuments, to identify connecting property-lines, names of owners, and registration of titles. They were also to note on the photographs other information necessary for the maps, such as names of places, streams, and other features.

In addition, certain stadia traverse-lines were run for the purpose of locating ground control-points for the plotting of the maps. A secondary system of triangulation was developed, in order to connect the different traverse-lines and establish a unified coordinate system for plotting the positions of the ground control-points.

The radial-line plotting of the maps was started last October, and already some 1,400 square km have been compiled in map-form on a scale of 1:25,000. Blue-prints of these maps are being prepared and will be sent into the field for checking and for the addition of missing data. After these corrections have been made on the original tracings, blue-line prints will be presented to the two governments for their work of arbitrating the territorial claims and selecting the definite boundary-line.

In order to provide accurate control for the monument-positions and for the drafting of the final maps, the precise system of triangulation along the Guatemala-Honduras boundary is being extended southwestward along the El Salvador boundary to the Pacific Ocean.

The reconnaissance-work on this extension was started in October 1936 and completed the following January. All station-monuments, reference-monuments, signals, and observing platforms were constructed during January, with the exception of three 60-foot towers, which are now being built at the stations of the base-net in the flat Pacific coastal regions at the southern end of the new system.

As in the previous work along the Honduran boundary, all triangulation-stations are marked with a surface and also a subsurface monument of concrete. A bronze plug with flat top is embedded deeply in the concrete. One to three reference-marks are established at each station, usually concrete monuments with bronze center-plugs.

The new system is strongly connected to the old work at two intervisible stations, both of which were occupied and angles observed to a third old station. Including the two occupied old stations, there are 19 first-order and 19 secondary stations in the new system. A 7-km base has been laid out in the flat coastal plain at the Pacific end of the system.

Seven quadrilaterals are required to connect the old work to the new base-line, one of the figures having a center-point with only one of its diagonals visible. The axial distance through the net is 120 km, and the strength of the figures, as computed from the reconnaissance-plot, gives the value for ΣR_1 as 40. Two first-order stations not needed in the control of the boundary have been located on the summits of prominent volcanos, Suchitan and Santa Ana, respectively in Guatemala and in El Salvador. These stations were located with a view to the future extension of the system into each country, as they will afford an excellent base, together with certain other stations, for starting any such extension work that may be contemplated.

Both governments have expressed the desire of obtaining a complete set of first-order observing equipment to be used on future internal surveys. The Commission has therefore purchased the following instruments, which will be used on the demarcation work and then divided equally between the two governments: Two Wild first-order theodolites, newly designed type No. 3, with electrical equipment for night observing and extra base-plates for placing the instrument on observing platforms--these instruments read direct to 1/10 of a second; two Zeiss second-order theodolites, type No. 2, reading direct to one second; twenty observing lights, made by D. Ballauf Company of Washington, D. C., in accordance with the specifications of the United States Coast and Geodetic Survey; six invar 50-meter ribbon tapes, made by Driver Harris Company, heat-treated by the Rensselaer Polytechnic Institute, and finished and graduated by the Keuffel and Esser Company--these tapes have been standardized by the United States Bureau of Standards; two 50-meter steel tapes for staking base-lines; two sets of base-line tape-stretching apparatus, made by D. Ballauf Company to the specifications of the United States Coast and Geodetic Survey.

The angle-observations on the new system were started on February 10, 1937, with two parties working on opposite sides of the chain of quadrilaterals. V. J. Hanrahan, who gained his experience in this class of work in 1935 under Lieut. Lushene and later, in 1936, did some additional first-order work with very satisfactory results, is in charge of field-work and is acting as observer in the first party. The second party is under the charge of a capable engineer, who, however, has had little experience in first-order observing. The latest reports from the field-parties indicate that the work is progressing very well, and the closures in the first figures are excellent.

Considerable trouble was experienced during the survey in 1935 with the intersections of the secondary stations. Plans had been worked out in the office to provide for at least three intersections on each of these points, but in the actual field-work a number of these points were only observed twice, with the result that the computations of their positions could not be checked by a second triangle.

In order to raise the standards of the secondary stations in the new work in 1937 to a higher grade of accuracy, it was decided to organize a third observing party for these secondary stations. This party is provided with a Zeiss theodolite, reading directly to one second. All secondary points are to be occupied by this third party, and sets of six directions will be observed on the primary stations. This procedure will provide ample data for computing the positions of these stations with second-order accuracy, even where two directions only can be obtained to a secondary point.

The secondary points are located at short intervals along the approximate boundary, and they will be used in the adjustment of the stadia-traverse of that line. The geographic positions of the intermediate monuments between these secondary stations will be obtained from the adjusted traverse-lines, in a similar manner to the methods used on the Honduran boundary.

The Commission was fortunate in being able to employ the same light-keepers who had worked with the former Commission on the survey of 1935. Some of the engineering students of the University of San Salvador are also being trained in this work, and recently this University published a small booklet containing the code-signals used in night-communication between the various field-parties on first-order work. Thus grows the local interest in this class of work.

The Commission is establishing a new astronomic and Laplace azimuth-station at the base-line on the Pacific Coast. Arrangements have been made with the United States Coast and Geodetic Survey for further cooperation in this astronomic work, and Lieutenant R. W. Woodworth has been detailed to conduct it. The Commission will pay all of the expenses, just as was done with the survey of 1935. The instruments were shipped on April 2 to a point on the Pacific Coast near the base-line, and Lieutenant Woodworth sailed from New York on April 17, 1937.

With this third astronomic position available for the adjustment of the provisional datum, it is hoped that corrections can be calculated for the deflection of the verticals at the three stations and that a more accurate value can be established for the basic datum of these surveys.

The writer believes that the Ocotepeque precise arc of triangulation, which extends from ocean to ocean across Central America, should be accepted as the basic geodetic control-net for all this region and that efforts should be made to have all future work of a precise nature in this area tied to this arc. With this belief, it is only natural to desire that every effort be made to establish an accurate geographic position for the base-station of this datum.

It would seem that the American Geophysical Union, and other organizations of similar nature, should be interested in the furtherance of this work, as the establishment of precise geodetic information throughout Central America will aid materially in many scientific studies.

During the past four years the writer has had many occasions to consult with the United States Coast and Geodetic Survey and also with the United States Geological Survey, concerning geodetic and mapping problems. He wishes to take this opportunity to thank both of these organizations as a whole, and also many of their individual members, for their kindness and extremely useful aid.

Comisión Mixta de Límites de El Salvador-Guatemala,
Guatemala City,
Guatemala

ANNUAL REPORT OF PROGRESS OF THE GEODETIC WORK OF THE COAST AND GEODETIC SURVEY

C. L. Garner

Geodetic operations in the United States are accomplished in the main part by the Coast and Geodetic Survey which is the principal agency for the extension of control-surveys consisting of triangulation and leveling, base-measurements, astronomical observations, gravity-determinations, and other operations incidental thereto. It has been reported at previous annual meetings that much control-work was accomplished by the Bureau during 1933, 1934, and 1935 through the use of emergency funds. Those funds were exhausted in July 1935 and, as our regular appropriations had also been curtailed meanwhile, geodetic operations were necessarily very drastically reduced at that time. Operations since then have been through funds made available through reduced regular appropriations, by transfer of funds from cooperative agencies, and by cooperation with the Works Progress Administration in several States.

Consequently, through these cooperative processes it has been possible to accomplish much very useful work in various States which will add materially to the control-net when the records are processed and adjusted into the Federal framework. The work accomplished by the Works Progress Administration organizations has been considerably more expensive than that accomplished through regular procedure, but it was not expected that the class of personnel thus obtained would operate as efficiently as our regular personnel who have been thoroughly trained in this class of work.

To April 1, 1937, approximately the following amounts of control and other surveying have been done in the United States during the more than 100 years of existence of the United States Coast and Geodetic Survey. (The progress-maps of the triangulation- and leveling-nets of the United States have been omitted from this year's report as they differ only slightly from those published in the Transactions for 1936.)

Amount of work accomplished

Item	During past year		Total	
	Miles	Stations	Miles	Stations
Triangulation	2800	1500	68,000	
Leveling	2570		261,000	
Geodetic astronomy				
Latitude		4		840
Longitude		4		691
Azimuth		3		1152
Gravity		75		755
Bases (total number)	209 first-order and 54 second-order			

During the past year the United States Coast and Geodetic Survey has cooperated with the Soil Conservation Service in the extension of first-order and second-order control in a number of areas in western states for the purpose of obtaining the necessary maps to be used by that organization in dealing with soil-erosion problems.

Cooperation was also extended to the United States Forest Service in Idaho and Montana where one field-officer was detailed for a period of about four months while establishing stations and making observations in the vicinity of Sand Point, Idaho. The purpose of this work was to determine the positions of fire lookout-towers as a means of obtaining more accurate fire-control.

Cooperation was extended to the Corps of Engineers, United States Army. Instruments and equipment were loaned to the District Engineers at Portland (Oregon), New Orleans (Louisiana), and Jacksonville (Florida) for projects of local control by the respective officers. A field-engineer cooperated with the District Engineer at Galveston, Texas, for the purpose of extending 247 miles of first-order levels in that region.

The United States Coast and Geodetic Survey has cooperated with Works Progress Administration organizations by detailing officers to serve in supervisory capacity in the field and office, to the end that field-control and computations thereof might be carried on in accordance with the standards of the United States Coast and Geodetic Survey as a means of placing the entire work in the Federal net. Such cooperation has been extended to Massachusetts, Connecticut, New Jersey, Westchester County of New York, Pennsylvania, Georgia, Florida, Arkansas, Oklahoma, and King County of Washington. Instruments and equipment were lent to these State organizations for carrying on their work. It is certain that the control-surveys furnish one of the best mediums for the employment of relief-personnel. The organizations engaged in these surveys know that the work accomplished is of lasting benefit to the citizens of the country, and undoubtedly the employees obtain some incentive from this fact.

The Bureau has continuously cooperated with the Advisory Committee in Seismology of the Carnegie Institution of Washington for a number of years in the extension of horizontal and vertical control-surveys, mostly in California, for the purpose of making certain studies relating to earth-movements involved in earthquakes. Due to the drastic decrease in the appropriations, it has not been possible to obtain desired control during the past year. In the summer of 1935, first-order levels were run over a series of bench-marks in nine different fault-zones in southern California, and it is planned to connect these bench-marks to the horizontal control-net of the country at the first opportunity. It is to be recalled that these bench-marks were very closely spaced, with intervals of 100 feet for the first mile away from the fault-zone, and with the interval increasing by 100 feet for each mile up to five. Therefore, a considerable amount of horizontal control-surveys will be required in order to connect these monuments rigidly into the control-net.

The Bureau also extended lines of first-order levels in the vicinity of Helena, Montana, last summer, for the purpose of studying possible earth-movements which may have resulted from the earthquake there in October 1935. This work was paid for from a special Public Works Administration allotment and was done with a view to repeating the observations in case of future disturbances.

For the sixth consecutive time, first-order levels are now being run over a small network in the region of San Jose, California, for the purpose of investigating earth-settlements of several years' duration. Most conspicuous among the evidence showing settlement was one or more well-casings in the region which continuously over a period of years apparently had risen out of the ground. One particular well extended to a depth of about 450 feet, which seemed to indicate that settlement was a surface one and did not extend deeply into the Earth. The results of the work so far indicate that altogether there has been a settlement in that region since the first line of levels in 1912 of approximately five feet, and according to unchecked information recently received from the field, it seems that some settlement is still going on.

The Bureau has also cooperated with a number of organizations in the extension of gravity-surveys. A field-party has been in continuous operation in the United States during the year and has made determinations at 75 new stations in Louisiana, Texas, Oklahoma, Alabama, Mississippi, and New Mexico. Twenty-five stations have been reoccupied. Particularly outstanding in the gravity-field is the cooperative expedition under the auspices of the United States Navy, American Geophysical Union, and the United States Coast and Geodetic Survey in obtaining values at a number of gravity-stations in the Caribbean Sea and the region of the Lesser Antilles, for which full details appear in other papers in these Transactions. In connection with this expedition, it is notable also that the timing of the gravity-pendulum was done by the use of a crystal chronometer which proved particularly valuable for this class of work. The Bell Telephone Laboratories of New York cooperated in the work of the expedition by furnishing this remarkable timepiece. Early in May 1937 it is planned to send a gravity-party to the field in the vicinity of Bethlehem, Pennsylvania, for the purpose of using the crystal chronometer for time-determinations in connection with gravity-observations on land. Apparently there is no reason why the crystal chronometer is not as well adapted to observations on land as at sea, and if the results obtained through the use of this timepiece are as successful as predicted, it is believed that we will be able to use it for similar observations in the future, and thus reduce to a negligible amount the errors entering into gravity-determinations because of uncertainties in time.

In 1935 the United States Coast and Geodetic Survey cooperated with the Guatemala-Honduras Boundary Commission by detailing an engineer and lending instruments as required to extend first-order triangulation and to make astronomical observations for the delineation of the boundary between those countries. It is of interest to note that this work has led to a similar request from the Mixed Commission for the Boundary between Guatemala and El Salvador for astronomical observations, including latitude, longitude, and azimuth, at one of their triangulation-stations near the Pacific end of the boundary. An engineer of the Survey is now en route to Guatemala to carry out his instructions covering this work.

At this time I desire to mention the splendid cooperation that has been extended the Bureau by the National Bureau of Standards in the standardization of instruments and equipment, and graduation of theodolite-circles, etc., similar to work that has been done by them in previous years. The Naval Observatory and the office of Naval Communications have also been particularly helpful to the Bureau in broadcasting radio time-signals whereby it has been possible for the gravimetric and astronomical field-parties to obtain the excellent time-signals which are so necessary for obtaining the accuracy required in gravity-work.

On two previous meetings of this Section, mention has been made of the plane coordinates devised by the United States Coast and Geodetic Survey for each of the 48 states and the uses of these coordinates have been explained. The object of devising plane coordinates was in order that the engineering and surveying professions throughout the country might have some common method of referencing their surveys so that the work in any region, when done in a permanent way, could be coordinated into the general system for the particular region, and thus made available for future use by others. Without question this plan is a means of obtaining uniform procedure and is thus a stimulus to the surveying profession in obtaining more accurate, reliable, and trustworthy surveys throughout the country. Spherical coordinates are not adaptable to small areas for various obvious reasons, but plane coordinates of some kind are of necessity used by all engineers and surveyors. The coordinates recommended for general use throughout the country are so devised as to furnish any desired scale of accuracy.

This system of plane coordinates has been adopted by the Federal Board of Surveys and Maps, and it has been recommended by the Board to map-making agencies of the Federal Government as a means of bringing about the objectives outlined above. Incidental to the same subject, it is gratifying to report that in several states the State planning-boards or other agencies have promoted the enactment of legislation legalizing the use of plane-coordinate systems in land-surveys and for the description of property. Property-boundaries thus coordinated with the national network can be recovered by a competent engineer at any time and it is obvious that a tremendous amount of litigation with regard to property-boundaries may thus be avoided.

Some progress has been made in the computation of the field-records during the past year, although it has not been possible by any means to make more than a small impression on the total amount of work to be done. Practically all of the records for the last year of the expanded program remain unprocessed, and naturally this work must be finished and put in some form for distribution before it becomes of any value.

It is particularly gratifying to note the many cooperative enterprises by various governmental organizations and that much is being accomplished through a more widespread spirit of cooperation throughout the entire Government fabric in recent years. It is believed that this applies to problems in general rather than to those in any particular field. However, cooperative surveys are not accomplishing satisfactory progress in mapping activities as viewed from the national standpoint. The principal and basic reason for control-surveys, which comprise the bulk of geodetic operations in this country, is for the purpose of establishing a framework on which to coordinate the mapping of the United States.

Despite the agitation of this question during the past half dozen years, there is less than one-half of the actual area of the United States covered by adequate maps. It is obvious that this condition should be remedied at the earliest possible opportunity. In January of this year the Secretary of the Interior recommended a mapping program to the President of the Senate, in response to a resolution of the Senate at the 75th session of Congress. The proposed program is on the basis of an average expenditure of five million dollars a year for a 20-year period, which would total a hundred million dollars. While there is no question but that a complete topographic map of the United States, including unmapped and inadequately mapped areas, will require expenditures in excess of the foregoing amount, it is quite certain that those sections of the country most in need of maps can be taken care of. Much interest is being centered on this proposal, but it is too early at this time to make any prediction as to what the final outcome will be.

The benefits to be derived from the mapping of the country are so obvious that it seems incredible that this or some other program will not soon be adopted. The control-framework is a prerequisite to the topographic mapping, which in turn is a prerequisite to fundamental planning preparatory to any major study of basic resources of our country. Maps are vital to the proper study of flood-control problems, irrigation, and numberless other public-works projects. Aside from these, they are particularly important for many scientific investigations. They have a direct bearing on many geological and geophysical problems of great importance in the study, use, and conservation of our natural resources, and it is inconceivable that these problems should not receive proper attention in the near future.

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AN ILLUSTRATION OF THE UTILITY OF STATE PLANE-COORDINATE SYSTEMS

Philip Kissam

In the minds of most persons there exists a psychological reaction against approximations. Approximations smack of rule of thumb. They introduce accidental errors that may accumulate and they are frequently dangerous if not used with thorough appreciation of their limitations. In the field of surveying and mapping, the measurements made in the field must be checked by geometry and reduced to a consistent geometric figure. As the shape of the Earth is not yet completely determined, any geometric check of field-measurements is bound to introduce a certain approximation. If the approximation is small enough, that is, considerably less than the probable resulting error, no harm can result.

Throughout the world, extensive instrumental surveys are invariably made by National and State governments rather than by individual enterprise. In the United States the surveying agencies chiefly engaged in extensive surveys, the United States Coast and Geodetic Survey and the United States Geological Survey, use as a basis for their geodetic work Clarke's spheroid of 1866. This approximation is so nearly coincident with the Earth's sea-level surface that the deviation may be neglected and it makes an ideal base upon which to determine the geometrical consistency of field-results.

On the other hand, by far the greater quantity of surveying in this country is executed by other agencies, public and private, over areas so small that a plane is a sufficiently accurate approximation to the Earth's surface to be used for determining the geometric properties of these surveys. When the Earth's surface is assumed to be flat, the computations are so simple and inexpensive that it is of considerable advantage to use a plane surface wherever possible, and it is therefore used so extensively that few engineers even understand geodetic reduction.

But as the entire United States is covered by a fundamental and accurate triangulation-net established by the United States Coast and Geodetic Survey, utilizing geographic positions for coordinates and therefore requiring geodetic reduction for utilization, the problem arises as to how this great system of triangulation can be utilized for checking, adjusting, and coordinating the results of plane surveys.

The answer to this problem is found in the State Plane-Coordinate Systems designed by Dr. O. S. Adams and introduced to the engineering profession by the United States Coast and Geodetic Survey. There is no reason to describe these systems in detail. Many articles and publications already exist defining these systems and explaining their use. It might be said that they are forms of the Lambert projection and the transverse Mercator projection. These projections of course introduce considerable approximations. There is bound to be a scale-factor which changes over a given area. However, the maximum scale-factor in nearly all of these projections is one part in ten thousand. But the accuracy of most surveys of the types produced by individual enterprise is usually not higher than this figure.

As pointed out before, the universality, consistency, and lack of approximation of reductions to a spheroid are so appealing that reductions to many plane systems seem abhorrent. But let us consider an illustration of the great utility of reductions to a plane.

There is a county-line in New Jersey appearing on the map as a straight line 20 miles long separating Camden and Gloucester counties on the northwest from Atlantic County on the southeast. It runs through a hitherto undeveloped district and its exact position has never been of great consequence. In recent years, however, with the development of highways, this area is becoming of greater financial importance. Beale M. Schmucker, County Engineer of Camden County, after a conference with the engineering staffs of the other two counties, became convinced that a new county-line should be marked, which was really a straight line, and as nearly as possible at the generally accepted position of the present line. Although a legislative act would be necessary to establish a new line, it was felt that the advantages of a straight line far outweighed the difficulties incurred.

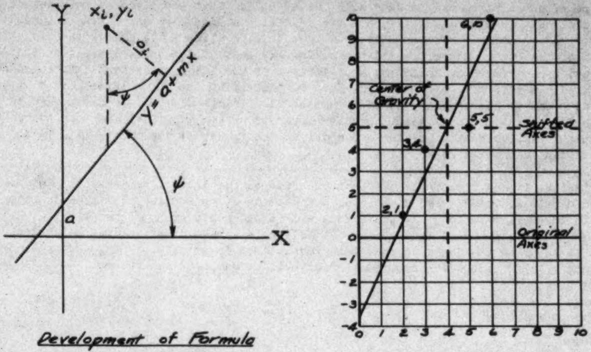
In order to carry out this scheme, a traverse-net was established consisting roughly of an elongated loop, 20 miles long and three miles wide, surrounding the county-line with cross-connections between the sides of the loop following each important road which crossed the line. At this time the United States Coast and Geodetic Survey established a triangulation-net straddling the county-line and many of the traverse-stations were used as triangulation-stations of this net. Where this was impossible, short traverse-connections were made with the triangulation-system.

In a case of this kind it would have been possible to compute the entire traverse-net by means of geographic positions on Clarke's spheroid. But had this been done, the traverse could not have been useful for plane-survey control unless the geographic position of traverse-monuments were reduced to plane coordinates. It was believed, and later proved, that the accuracy obtained by using geodetic reduction would so little enhance the accuracy that the inaccuracies of the traverse would far outweigh the advantage gained. It was therefore decided to utilize the State Plane-Coordinate System throughout.

While running the traverse some six old county-line monuments were recovered. These were tied to the traverse and their plane coordinates thus determined. It was evident from these coordinates that the old monuments marked a line which was far from straight and the problem arose as to the proper location of the new line and just what form of "straight" line should be adopted.

Taking up the last question first, the position of the mid-point of the line connecting two ends of the tri-county line was determined; first by geodetic methods, and then by computing the plane coordinates of the geographic position thus found. The plane coordinates of this point were then determined by averaging the coordinates of the two ends. The total distance between the two points, as expressed by the coordinates thus computed, was 0.17-foot or 0.12-foot between the lines. Such a test seems to indicate to the writer that for this particular purpose plane coordinates not only simplified all calculation but could produce accuracy of location far beyond the precision of any survey.

To find the proper position for the line was the next problem. After considerable search, copies of the original field-notes were found which indicated that the surveyor had attempted to establish a straight line. With this assumption it was felt that the line should be a straight line on the plane system such that the sum of the squares of its rectangular offsets to the ex-



Development of Formula

Let equation of County line be

$$y = a + mx \qquad m = \tan\psi$$

$$a_i = \frac{y_i - a - mx_i}{\sqrt{1+\tan^2\psi}}$$

$$\text{Let } U = \sum_1^n\left(\frac{y_i - a - mx_i}{\sqrt{1+\tan^2\psi}}\right)^2 = \sum_1^n\left(\frac{y_i - a - mx_i}{\sqrt{1+m^2}}\right)^2 \qquad [1]$$

Differentiating with respect to a and equating to zero

$$a = \frac{\sum_1^n y_i}{n} - m\frac{\sum_1^n x_i}{n} \qquad [2]$$

This shows line must pass through the center of gravity of mon. positions. To find m eliminate a by shifting Axes to center of gravity, Eq[1] becomes

$$U = \sum_1^n\left(\frac{y_i - mx_i}{\sqrt{1+m^2}}\right)^2$$

where x_i and y_i are now coordinates with respect to the center of gravity. Differentiating with respect to m and setting equal to zero

$$m^2\sum_1^n x_i y_i + m\left(\sum_1^n x_i^2 - \sum_1^n y_i^2\right) - \sum_1^n y_i x_i = 0$$

$$\text{Let } p = \sum_1^n x_i^2 \;;\; q = \sum_1^n y_i \;;\; r = \sum_1^n x_i y_i$$

$$m^2 + \frac{p-q}{r} - 1 = 0$$

Example of Solution

x_i	y_i	coord. shifted x_i	y_i	x_i^2	y_i^2	$x_i y_i$
2	1	-2	-4	4	16	+8
3	4	-1	-1	1	1	+1
5	5	+1	0	1	0	0
6	10	+2	+5	4	25	+10
Av. 4	5	Sum 0	0	p=10	q=42	r=19

$$\frac{p-q}{r} = \frac{10-42}{19} = -1.6842105$$

$$m = \frac{-1.6842105 \pm \sqrt{2.83656500831025 + 4}}{-2}$$

$$= 2.1494465 \qquad \text{Slope}$$

Substituting value for m in Eq [2]

$$a = 5 - 4 \cdot 2.1494465$$
$$= -3.5977860$$

Equation of required line

$$y = -3.5977860 + 2.1494465\,x$$

FIG. 1

isting monuments should be a minimum. In other words, the method of least squares should be applied. Again computation was simplified by means of plane coordinates. The formula shown in Figure 1 was used. It was necessary only to set up a table as shown in Figure 1 to determine the slope of the line, while the average of the coordinates gave a center of gravity through which the line should pass.

A bill is now in legislature establishing this line as the final boundary and a field-party is at work placing monuments along it. The line could be completely described by giving the equation of the line in terms of plane coordinates; or, as was adopted for the legislative bill, the usual type of description can be used with the exception that the plane coordinates of the beginning and end of the line was stated and the direction of the line was given in terms of grid-bearing. No attempt was made to utilize a true bearing which would change throughout the entire length of the line. Since the line is definitely part of the State Coordinate-System even to its bearing, any surveyor establishing a property-line who has had the foresight to connect his traverses with a pair of coordinate-monuments can determine the exact intersection of the county-line with any of his boundary-lines by computation in his office. In fact, marking the actual county-line is unnecessary with the many monuments on the two traverses near the county-line because from the coordinates of the monuments on the traverses the county-line is absolutely determined and can be located at any time.

In conclusion, it may be pointed out that in spite of the lack of mathematical "nicety," the plane-coordinate system offered a base for computation of an accuracy far greater than the survey used in this illustration. It provided a simple and rapid means of determining the relative positions of the old county-line marks. It offered a simple least-squares adjustment for the position of the line and now affords all surveys within three miles of the county-line with accurate points of reference which can be utilized without geodetic reductions.

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GRAVITY-ANOMALIES AND GEOLOGIC STRUCTURE

George P. Woollard

Introduction

In projecting geologic structure from areas of known geology into regions of unknown geology it appears advisable to use a combination of gravitational and seismic methods. This is because the inherent defects of each considered alone are to a large measure eliminated by the supplementary information supplied by the other when used in conjunction. However, since at the present time the gravitational information represents other factors than just geology, it is necessary that the various components be ascertained so that their effect may be taken into consideration and the anomalies reduced for interpretation to just that portion due to geologic factors. With this purpose in view, a gravitational analysis is presented in which an effort has been made to ascertain the exact nature of the anomaly-control and also a line of attack for future investigation is presented whereby it is hoped that it will be possible to derive gravity-anomalies reflecting only the geologic factors.

Causes of anomalies

It appears from the writer's previous work [see 1 of references at end of paper], as well as that of Chamberlin [2], Longwell [3], Bullard [4], and Swick [5], that there are four princi-

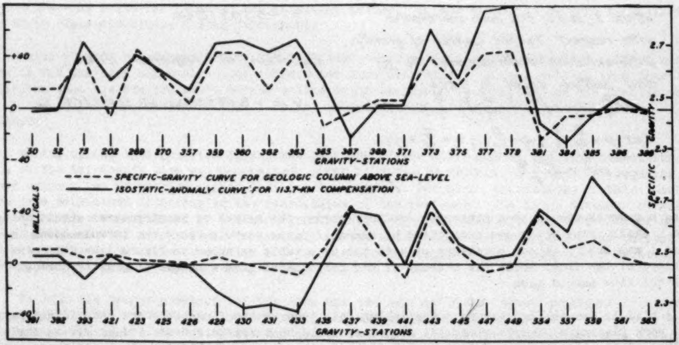


FIG. 1—SPECIFIC-GRAVITY AND ISOSTATIC-ANOMALY CURVES

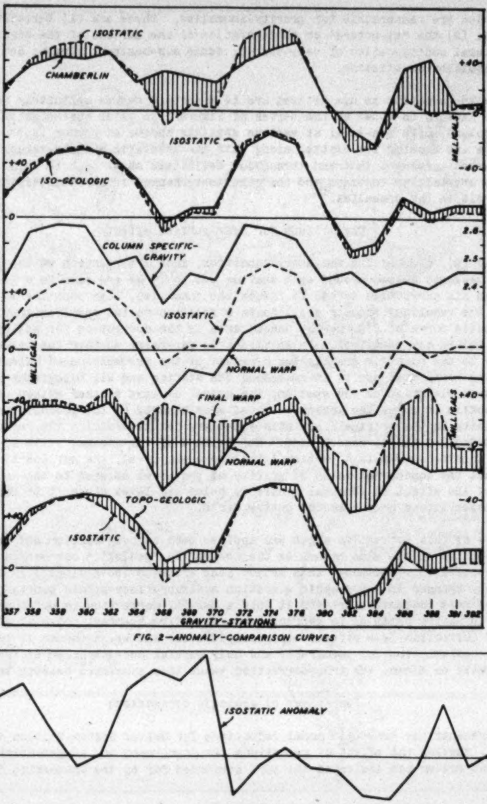


FIG. 2—ANOMALY-COMPARISON CURVES

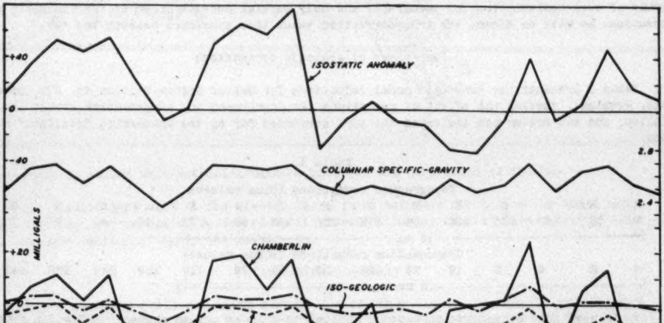


FIG. 3—CORRECTION-CURVES FOR GEOLOGY

pal factors which are responsible for gravity-anomalies. These are (1) Variations in near-surface densities; (2) the "structure" or configuration of the surface of the crystalline basement; (3) the structural configuration of deep-seated, dense sub-basement strata; and (4) the degree of isostatic equilibrium existing.

That gravity-anomalies as now derived are to a certain degree definitely related to the above geologic factors is shown by the curves of Figure 1 in which the weighted mean density for the geologic column above sea-level at various stations chosen at random in the Bighorn Basin Area of Montana and Wyoming are plotted along with the isostatic anomaly-values at the same stations. The marked agreement in trend throughout definitely shows that in this Area the configuration of the crystalline basement and the resultant changes in surface-density variations play an important role in the anomalies.

Corrections for near-surface effects

Chamberlin [2], recognizing the above condition, made a correction to the isostatic anomalies for the geologic column around each station out to 16 km and down to 8 km below the surface. Although his correction serves to reduce the anomalies, both positive and negative, towards zero, the resultant anomaly still bears a relation to the specific-gravity curve (see geologic-isostatic curve of Fig. 2--the shaded area is the correction for geology as computed by Chamberlin on 113-km compensation). In an effort to determine whether the relation of this residual anomaly to the specific gravity was a result of the assumptions of calculation, namely, all strata lying horizontal out to 16 km around the station and all topography within this area being at the same elevation as the station, the writer devised another method of computing the geologic correction in which the actual weighted mean density of the geologic column was effectively substituted in the original isostatic equations for determining the reductions for topography and compensation out to zone O (166.7 km) instead of the assumed value of 2.67. The geologic column considered was that portion lying above sea-level, the surface of the geoid. It was assumed that the equatorial value of gravity at sea-level as used in the international formula [6] embodied the effect of abnormal densities below sea-level since it is empirically derived from gravity-observations made over the entire Earth.

The effect of this correction which was applied both to compensation and topography was to reduce the anomalies in the same manner as the Chamberlin "geologic" correction only to a much less degree (see Fig. 3). Although this method (the writer's iso-geologic) is believed to consider accurately changes in topographic elevation and subsurface-strata configuration, the writer in the light of this analysis considers it only a partial correction in not considering the geologic column to such a depth as to embrace the crystalline basement-rocks at all points. Since the "geologic" correction does effectively accomplish the latter, although it is too large as a result of over-compensation for topography and only partial consideration of the isostatic compensation, as will be shown, the true correction value lies somewhere between the two.

Comparison of geologic corrections

Table 1 presents the isostatic zonal reductions for United States Station No. 372 (Steamboat, Wyoming), showing the effect of reductions for topography and compensation around the Station, and the writer has indicated the part corrected for by the Chamberlin "geologic" correction.

Table 1

Topographic reductions (plus values)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
2	68	163	336	490	454	312	234	188	95	73	48	44	9	7

[←——————16 km——————→]

Compensation reductions (minus values)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	2	4	9	19	24	28	37	59	79	110	159	348	238	241

[←——————16 km——————→]

It is seen that a geologic correction applied to a 16-km column around the Station embraces the bulk of the topographic effects but omits most of the compensation which is of opposite sign to the topography, thus yielding a corrective factor that is too large.

The above is also indicated when comparative curves are plotted for the geological corrections arrived at by the Chamberlin method and that of the writer and an additional curve inserted for only the topographic portion of the writer's correction. This latter curve, the topo-geologic curve of Figure 3, bears a marked correlation in trend to the "geologic" correction-curve despite

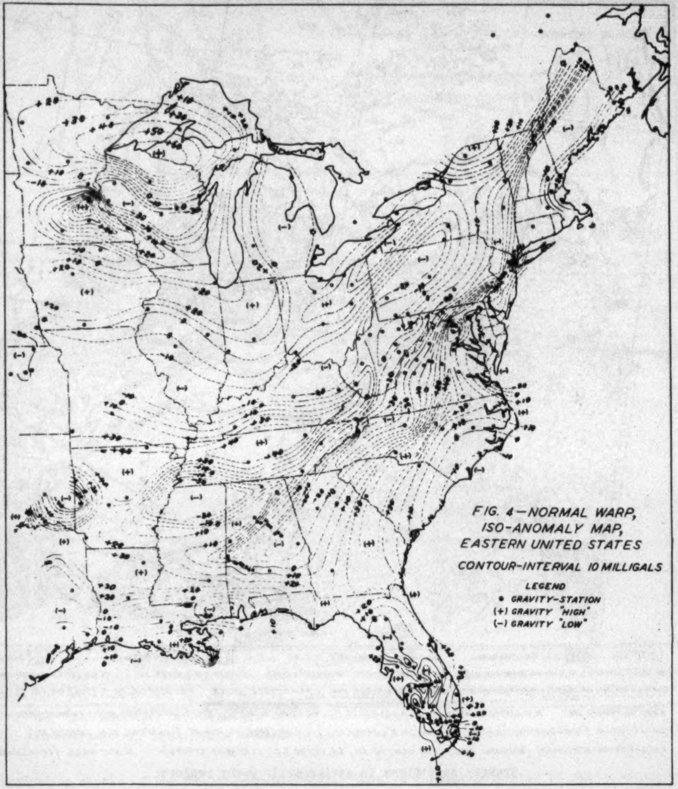


FIG. 4—NORMAL WARP, ISO-ANOMALY MAP, EASTERN UNITED STATES

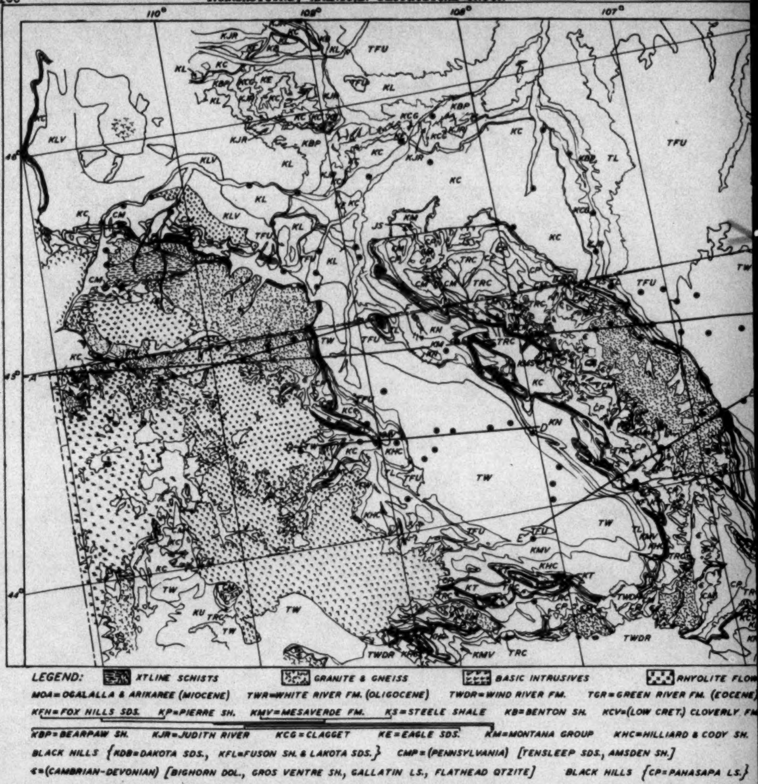
CONTOUR-INTERVAL 10 MILLIGALS

the differences in the mathematical treatment used for the derivation of the two.

These results show that at the present there is no accurate correction for these near-surface factors, but an approximation of their effect is had in that it lies between Chamberlin's value and that value derived by the writer.

The residual anomaly

The large anomaly still remaining must be due to other causes, presumably sub-basement structures and the lack of isostatic equilibrium. If isostasy is real, and there is abundant evidence in support of it, then a gravitational analysis in some geologically stable area, as a shield-area, should yield information on the deep-seated sub-basement effects, as in such an area isostatic equilibrium should be attained. Conversely in an area believed to be out of isostatic equilibrium, as in some of the geologically young regions, it should be possible to study isostatic effects by correcting for the near-surface geology. That this proposed division for the areal study of isostasy and geology through the medium of gravity should possibly be further subdivided into topographic provinces as the oceanic basins, sea-level areas, and mountain-regions, appears desirable in that our present knowledge concerning regional topography and isostasy are still rather vague.


110°
109°
108°
107°
46°
45°
44°
A
D
E
KJR
KC
KL
TFU
KLV
KBP
KCG
KE
KM
KN
TRC
CP
CM
TW
TL
KMV
KHC
KT
TWDR
KU
JS
LEGEND: XTLINE SCHISTS
GRANITE & GNEISS
BASIC INTRUSIVES
RHYOLITE FLOW
MOA=OGALALLA & ARIKAREE (MIOCENE) TWR=WHITE RIVER FM. (OLIGOCENE) TWDR=WIND RIVER FM. TGR=GREEN RIVER FM. (EOCENE)
KFH=FOX HILLS SDS. KP=PIERRE SH. KMV=MESAVERDE FM. KS=STEELE SHALE KB=BENTON SH. KCV=(LOW CRET.) CLOVERLY F
KBP=BEARPAW SH. KJR=JUDITH RIVER KCG=CLAGGET KE=EAGLE SDS. KM=MONTANA GROUP KHC=HILLIARD & CODY SH.
BLACK HILLS {KDB=DAKOTA SDS., KFL=FUSON SH. & LAKOTA SDS.} CMP=(PENNSYLVANIA) [TENSLEEP SDS., AMSDEN SH.]
Є=(CAMBRIAN-DEVONIAN) [BIGHORN DOL., GROS VENTRE SH., GALLATIN LS., FLATHEAD QTZITE] BLACK HILLS {CP=PAHASAPA LS.}

Gravity-conditions in geologically young regiors

That in geologically young regions the deep-seated effects will exert only a minimum influence is regarded as likely due to the proximity of marked variations in near-surface structure and consequent surface-variations in density to the point of gravity-observations and their resultant predominant effect. That this is true in the Yellowstone-Bighorn Region is indicated by not only the gravitational work there but in other localities. Bullard [4], in his gravity-investigations of the Rift valleys of East Africa, shows that the fault-bounded valleys, which are seldom occupied by sediments and frequently floored by the "basement" rocks, are characterized by marked gravity "lows" which have sharp contacts. This he has interpreted as indicating a light crustal block being forced down and restrained under stress and therefore definitely out of isostatic equilibrium. In the Yellowstone-Bighorn Region the break in the anomaly-profiles is similarly quite sharp. Here the Beartooth Mountains and the Bighorn Mountains, two gravity "highs," are both characterized by sharp breaks in the gravity-profiles when their fault-bounded flanks are crossed, and that this gravity-change can not all be attributed to the density of the crystalline rocks forced up to form the mountains the writer has just indicated. If the large resultant anomalies were due to deep, sub-basement structures, the gravitational effect would be spread out over a considerable area, but, as it is, the breaks are quite sharp and, it is believed, can only be attributed to lack of isostatic equilibrium. In this case this is a result

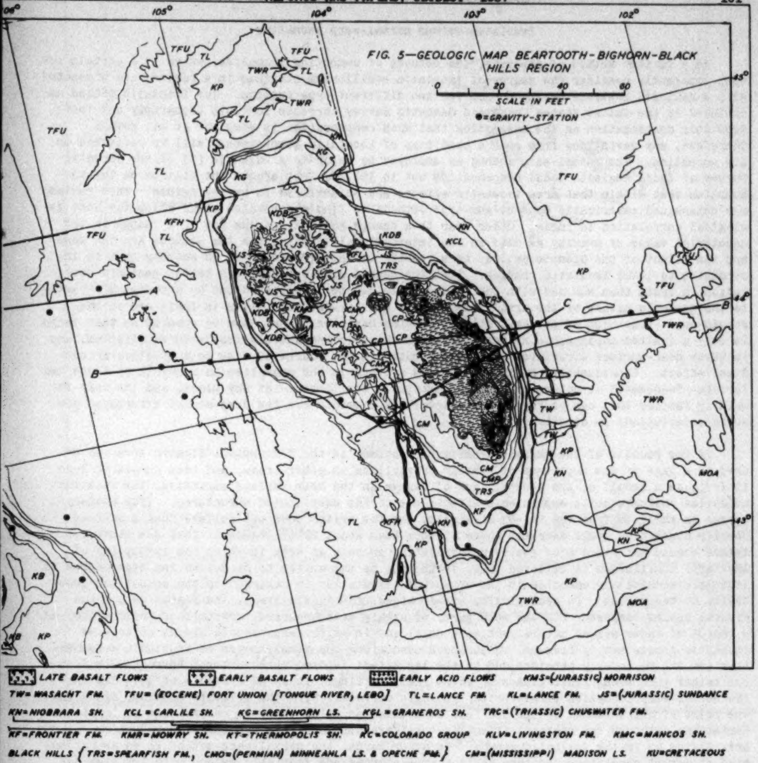


FIG. 5—GEOLOGIC MAP BEARTOOTH-BIGHORN-BLACK HILLS REGION

106°
105°
104°
103°
102°
45°
44°
43°
0 20 40 60
SCALE IN FEET
● = GRAVITY-STATION
A
B
C
TFU
TL
TWR
KP
KG
KN
KFH
KDB
JS
TRS
KCL
KFL
CP
KNO
TRC
KMS
CM
CMO
TW
KF
KB
MOA
LATE BASALT FLOWS
EARLY BASALT FLOWS
EARLY ACID FLOWS
KMS=(JURASSIC) MORRISON
TW=WASACHT FM.
TFU=(EOCENE) FORT UNION [TONGUE RIVER, LEBO]
TL=LANCE FM.
KL=LANCE FM.
JS=(JURASSIC) SUNDANCE
KN=NIOBRARA SH.
KCL=CARLILE SH.
KG=GREENHORN LS.
KGL=GRANEROS SH.
TRC=(TRIASSIC) CHUGWATER FM.
KF=FRONTIER FM.
KMR=MOWRY SH.
KT=THERMOPOLIS SH.
KC=COLORADO GROUP
KLV=LIVINGSTON FM.
KMC=MANCOS SH.
BLACK HILLS {TRS=SPEARFISH FM., CMO=(PERMIAN) MINNEAHLA LS. & OPECHE FM.}
CM=(MISSISSIPPI) MADISON LS.
KU=CRETACEOUS

of wedged-up blocks of the dense basement-rocks. This is further supported by the observed high density of the rocks composing these mountains, in contrast to the isostatic idea that the mountains are characterized by a deficiency in mass. Unfortunately, as far as the writer is aware, there are no deflection-of-the-vertical observations in this Area to offer additional evidence on this score, but it is believed that, if they were established, the above contention would be amply supported. That a part of this resultant anomaly is due to minor causes such as the difference in elevation represented by the spread between the spheroid and the geoid (Bowie effect), etc., is undoubtedly true, but these changes are all of a regional nature, serving only to raise or lower the anomalies by constant values with little change in the relative values now observed.

In contrast to the above examples Longwell [3] found, in making his analysis of the gravity-observations in the Connecticut Valley, that the gravity-anomalies bore little recognizable relation to the known crystalline basement-surface bounding the Triassic trough, but rather reflected a much deeper structure of much wider extent than the basement-structure. In this case the area is of sufficient geologic age that lack of isostatic equilibrium is regarded as being no great factor and, if it were, the closeness of the gravity-control would show the anomaly-breaks limited to the fault-block with sharp contacts rather than a more regional thing with gradual contacts and bearing no relation to the trough.

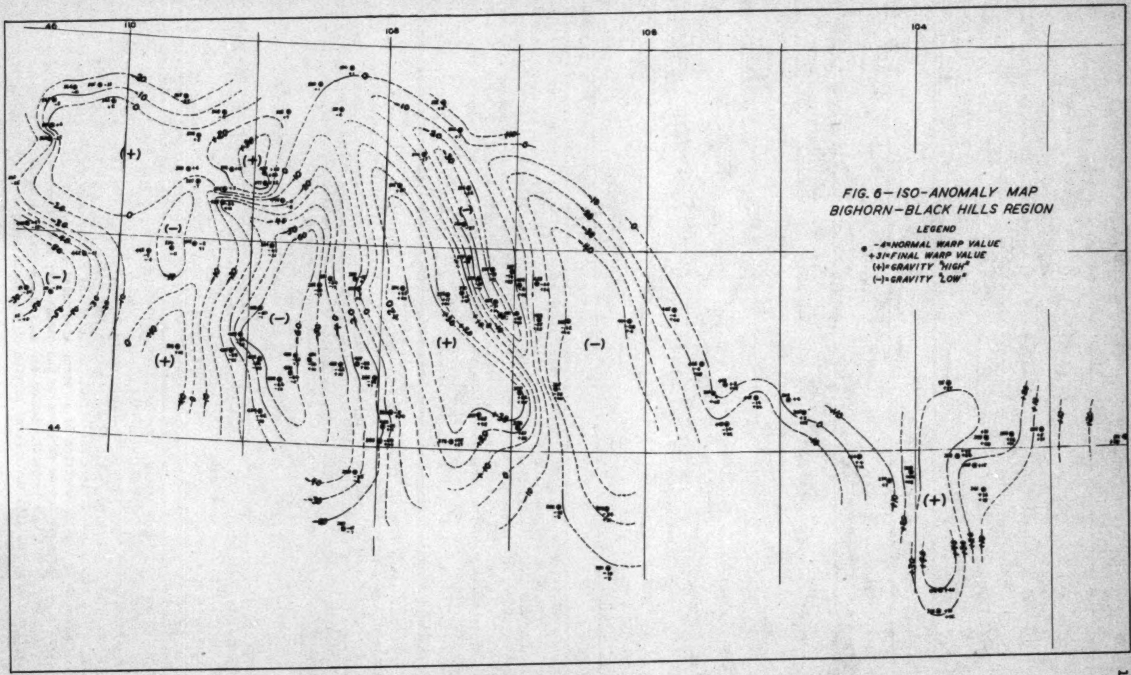
Isostatic versus normal-warp anomalies

As a further method of analysis, two methods of computing anomalies, which to a certain extent apparently consider the degree of isostatic equilibrium attained in a region, are presented with a geologic analysis based on each for two different type regions. The isostatic method as employed by the United States Coast and Geodetic Survey corrects for both topography and local isostatic compensation on the assumption that such compensation is complete at all points. Therefore, any deviations from such a condition of isostatic completeness will be reflected in the anomalies. The normal-warp method as employed by Major E. A. Glennie [7] of the Geodetic Survey of India neglects local compensation out to 120,000 feet around the station on the assumption that within that area isostatic effects are so small as to be negligible. This radius was determined empirically by "cut-and-try" methods to find which value would allow the best geological correlation in India. Other than this change and a minor one due to a change in the equatorial value of gravity as used in the international formula, the two methods are the same and the effect of the Glennie method, as a result, is the derivation of an anomaly that is insensitive to local isostatic changes. That the method should offer much better geologic correlation in India than was had with the isostatic values it is believed can be attributed directly to the geologic nature of the area. Most of the gravity-determinations in India are on the shield-area--that area of geologic stability which has been planed down by erosion so that there is only a limited topographic relief, for which there is undoubtedly isostatic equilibrium, and in which near-surface structures have been reduced in the course of time to a practically constant effect. Consequently, no marked changes are had in the anomalies as a result of these two factors--"basement" structure and lack of isostatic equilibrium--at any place, and the only remaining factors that can be regarded as disturbing elements are the deep-seated structures and surface-variations in density.

If the results of the surface-density corrections in the Yellowstone-Bighorn Area can be used as a gage of the magnitude of similar corrections in other areas, and they should be less in India as a result of the general lack of change in the near-surface structure, the resultant anomalies indicate quite appreciable effects due to the deep-seated structures. (The anomaly-spread in India is from +80 to -80 milligals, and the writer does not believe that a surface-density correction would decrease these by more than about 20 milligals.) That the isostatic method should not yield good geologic correlation in such an area in which the assumption of isostatic equilibrium is believed true, is thought by the writer to be due to the high degree of isostatic sensitivity embodied in the method of computation in contrast to the actual low sensitivity of the region. In geologically stable areas, the shield-areas, the region is a thick crustal nuclei composed, for the most part, of highly metamorphosed, crystalline rocks which, as a result of their welded nature, act as a unit, and in which responses to stress as well as isostatic forces are by flexure. Under such conditions the completeness of isostatic compensation can not be locally attained due to the lag-effect imposed by adjustment through such flexure rather than along fault-planes or short-radii folding. It is as a result of this lag that the normal-warp anomalies permit better geologic correlation, in the writer's opinion, since any one point within a radius of 120,000 feet is treated as being entirely insensitive to isostatic variations although the regional effect is considered by using the compensation-reductions beyond this radius as in the isostatic method. In other words, the normal-warp method is an approximation of actual conditions for this type of area whereas the isostatic method with its high degree of accuracy apparently introduces an error by correcting for conditions that are not locally attained.

No other explanation appears to the writer to adequately explain the apparently better correlation obtained by this method over the isostatic method in India. That the same relations apparently hold true in the United States are seen by a comparison of the iso-anomaly maps constructed by the writer on the two bases. In a former analysis [1] he called attention to the lack of correlation between the isostatic values and the geology in two areas of the covered Canadian shield, the Michigan Basin and the Ozark Region. The present iso-anomaly map on the normal-warp basis (see Fig. 4) allows a geologic correlation with these areas, and in no place where there was geologic correlation with the isostatic values does there appear any conflict using the normal-warp values. Since the geologic structures reflected are regional ones, it would appear that the crustal-warp hypothesis (that anomalies are the result of warpings of the outer crustal layers of the Earth, that is, granite, basalt, and peridotite as postulated by seismologists for respective depths of 10 and 30 km below the surface) is substantiated for the North American shield-area as far as examined, as well as in India.

That the normal-warp anomalies would not yield as good a geologic correlation in areas where local response to isostatic forces is attained is believed true. Although there is no area to the writer's knowledge considered by geologists to be both in isostatic equilibrium and also



46
110
108
106
104
44
(+)
(−)
LEGEND
● −4 = NORMAL WARP VALUE
+31 = FINAL WARP VALUE
(+) = GRAVITY "HIGH"
(−) = GRAVITY "LOW"

FIG. 6 — ISO-ANOMALY MAP
BIGHORN — BLACK HILLS REGION

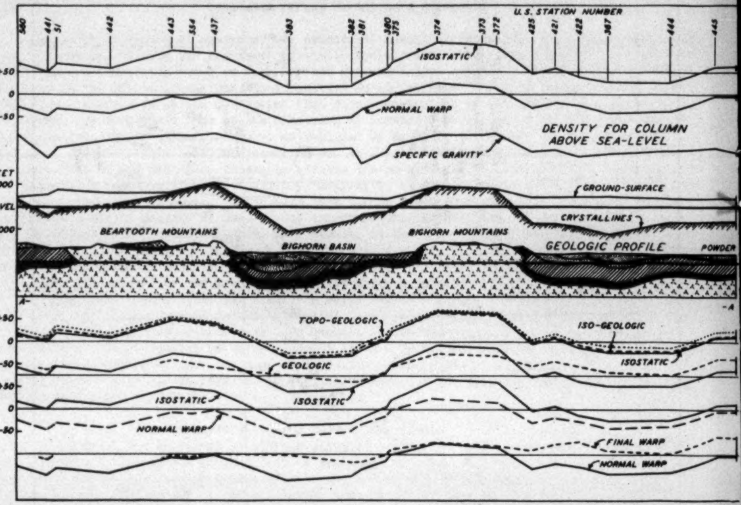


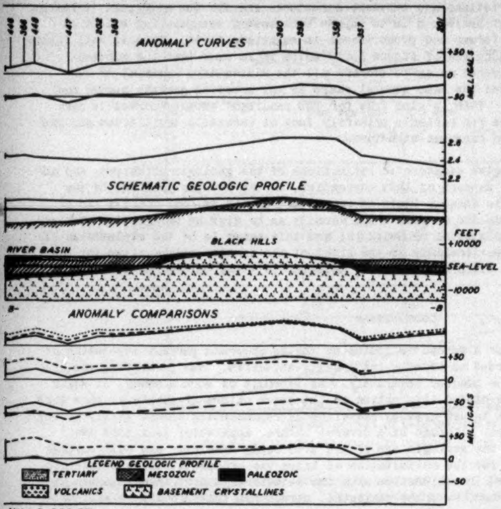
FIG. 7—GRAVITY-PROFILES BIGHORN-BLACK

of such a nature as to allow the completeness of local isostatic adjustment desired, an indirect test can be applied by testing an area believed to be out of equilibrium and in which there is apparently local adjustment such as the Bighorn Basin Region. Here, as previously pointed out, the sharp breaks in the anomaly-curves are attributed directly to the marked changes in three of the controlling factors, namely, surface-density, "basement"-structure, and isostatic inequilibrium. By the nature of the normal-warp method the third factor--degree of isostatic equilibrium--should not be reflected by anomalies on this basis as well as with the isostatic values. That this is the case is shown by the iso-anomaly maps and gravity-geologic profiles constructed for the Yellowstone-Bighorn Region (see Figs. 5, 6, and 7).

The normal-warp anomaly-correlation with the geology is inferior on the whole and in part non-existent, whereas a marked geologic correlation was obtained using isostatic values. (The isostatic iso-anomaly map was published in reference [1] and is not reproduced here.) The gravity-profiles, in addition to the methods discussed so far, include a final warp-anomaly profile which is the normal-warp anomaly plus a geologic correction based upon Prof. Chamberlin's correction, only with all compensation-effects entirely eliminated.

Indications of the analysis

The above evidence, as far as it goes, would indicate that, for an adequate geologic analysis by gravity, two methods and also the areas to which they are applicable should be borne in mind. In geologically young areas it appears that the topographic features are most frequently the expression of isostatic inequilibrium and the fundamental structure of the region (here basement-structure), and this structure is best reflected by the isostatic method employing local compensation. Isostatic deviations thus recorded bear a definite relation to the structural features as shown by the writer for the Yellowstone-Bighorn Region and by Bullard for the Rift valleys of Africa. In geologically old areas, as the shields which are the nuclei about which the continents are formed, there is a local lag in the crust's response to isostatic forces due to the nature of yielding by gentle flexure rather than sharp folding or faulting. The result is that non-consideration of this lag-effect, although the region as a whole is in equilibrium, leads apparently to the introduction of an error when local compensation is employed. That the neglect of local compensation as employed in the normal-warp method gives better geologic correlation than is had with the isostatic method for such areas has been shown for the shield-area of India by Glennie and also the covered portion of the North American Shield by the writer.



HILLS REGION

In the geologically young areas the geologic structure reflected is that of the near-surface basement. This is primarily due to the proximity of the basement-structure to the station and the magnitude of its own and consequent effects. In geologically old areas the geologic structure reflected is that of deep-seated sub-basement structures, as the near-surface structures have been reduced by the leveling process of erosion and time both physically and isostatically to an apparently constant factor for the area. The deep structures, as pointed out, are thus brought into prominence by the elimination of the other causal factors.

Although the above explanations are advanced as suggestions, which may or may not be substantiated by future work, the principal problem is still to reduce the anomalies to such a point that they will reflect primarily only geologic factors. In order to do this it appears to the writer that it will first be necessary to eliminate as many of the known factors as possible in order to study the unknown effects. With this in mind, a more complete correction would be made for near-surface density-variations that will carry down to the crystalline basement at all points and thus embrace not only the effects of the basement-configuration but also the effect of density-variations in the overlying sediments.

Methods for future study

In order to do this, two methods have been proposed. One is to reduce the spheroid of reference by perhaps 10 km in radius so that its surface at all points would lie below the crystalline basement-surface, and then correct for the overlying geologic column similar to the present method of correcting for topography above sea-level. The other method is to make an additional correction to that devised by the writer for the topography above sea-level, in which a similar correction would be applied for the geology below sea-level to such a depth as to embrace the basement-rocks.

Of the two methods the latter, which was suggested by Mr. Swick of the United States Coast and Geodetic Survey, apparently is the better since it involves no change in the international formula, which would have to be completely rederived under the other method and thereby introduce perhaps additional mathematical errors.

Once this correction for near-surface geology is completed, it will then be possible to study the resultant anomaly from the viewpoint of completeness of isostatic equilibrium and the effect of deep structures and, as pointed out, the two effects can be separated by observing the reflection of the depth-factor as shown in the sharpness of the gravity-breaks using a close network of stations. The effect of deep-seated structure would be to have no sharp breaks since the distance-factor would distribute the disturbance over a considerable area at the surface.

In this way it will be possible for the first time to really make a comprehensive study of isostasy since contributing factors which are reflected both in gravity and deflection-of-vertical observations will be separated, leaving, it is believed, only that part due to isostasy. To elaborate on this point, any one of the four forces listed as causing anomalies can give the same anomaly-curve with the other three factors held constant, and therefore that part due to each can only be determined by a separation as outlined above.

Although surface-density variations and basement-structures are for the most part intimately associated, the effect of light-sediments is to impose a secondary exaggerating effect on the fundamental curve due to the former and proportional in magnitude to it. This is well illustrated in the geologic correction-curves of Figure 3, in which it is seen that the surface-density correction, whether considered so as to embrace all the sedimentary material or just that portion above sea-level, gives the same general shape as the specific-gravity curves and also the isostatic-anomaly curve. This is also true for the resultant anomaly-curves in both cases, as shown in Figure 2, where one reflects primarily lack of isostatic equilibrium and the other both lack of equilibrium and basement-structure.

These compound-effects thus give exaggerated reflections of the geologic structure, and additional examples may be cited in support of this contention, as the steeper gradient of the gravity-profile across the Atlantic Coastal Plain in comparison to the seismic profile run by Ewing [8]. That the sediments here are of such a low density as to give an exaggerated gradient to the basement-profile has been suggested by Swick [5] and this seems to be the explanation of at least part of the divergence, particularly in the light of the density-values given for the sediments of the Atlantic Coastal Plain for Brazil by Malamphy [9]--the values run from 1.6 to 2.0.

Conclusions

In conclusion, it appears that a method is indicated for an accurate partial separation of the various factors that are regarded as causing the gravity-anomalies, thus permitting the effect of these various factors to be studied separately. As a result of such a study, it would appear to be possible to gain much-needed information on the exact nature of isostasy; once this is known it would then be possible to use gravity-anomalies as representing almost purely geologic factors. These geologic factors, although of a diverse nature, apparently fall into two fundamental groups depending upon the geologic age of the area being examined, and with further investigation the exact treatment for the delimitation of these two groups is believed possible. Finally, with such information used in conjunction with the seismic method of investigation to supply the needed actual depth-factor, accurate geological structural interpretations will be possible in areas of unknown geology.

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ACCURACY OF MODERN GRAVIMETER-MEASUREMENTS

Donald C. Barton and W. T. White

The accuracy of the Humble Oil and Refining Company gravimeters, instruments A to E, is represented by a probable error of ± 0.093 ± 0.003 milligal for the determination of Δg between base-stations. The routine practice in the Company's field-work with these gravimeters is to start from a base-station, A, in the morning and take stations every 2/3, 1, or 1-1/2 miles for 3-1/2 to 7 miles; another base-station, B, is then occupied; a quick return is made back to base A; and a second trip is made to B, taking all intermediate stations over again. The drist of the instrument is calculated both from the double observations on A and those on B. The final value of Δg from A to B, therefore, is based on three partially independent runs between the base-stations. The probable error stated above refers to the accuracy of that value for Δg between A and B. The set of runs between A and B is referred to in this paper as a link.

Fifty independent closed traverses were selected from the field-sheets in preparing the graph shown in Figure 1. All the longer traverses available were used. The rest of the traverses were taken without selection, except that a few were rejected because the men handling the

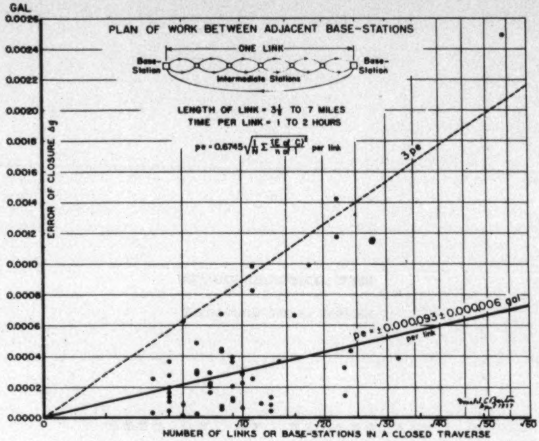

FIG. 1—ACCURACY OF HO&R CO. GRAVIMETER IN ROUTINE FIELD-WORK

data seemed to have valid reasons other than poor errors of closure for regarding the instrument as out of order or out of adjustment. The respective errors of closure and number of links in the traverse were used in the following formula to obtain the probable error of the determination of Δg over a link.

$$\text{p.e.} = 0.6745 \sqrt{(1/N) \sum [(E \text{ of } C)^2]/(n \text{ of } \ell)}$$

where N = number of traverses, E of C = error of closure, and n of ℓ = number of links in a traverse. The accompanying graph shows the error of closure plotted against the square root of the number of links in the traverse.

The data are from the work of several instruments. Some of the closed traverses were run with one instrument, but many were built up from the work of more than one instrument. The length of most of the links in these traverses lay in the range 3-1/2 to 7 miles.

The time spent on most of those links ranged from 1 to 2 hours. That time covers the interval from the beginning of the first observation on base-station A to the second observation on base-station B. During that time four observations are made on two base-stations and eight to sixteen observations on half as many intermediate stations.

The overall-error of closure in these 50 traverses was greater than 1.0 milligal in only three traverses, and was greater than 1.5 milligal in only one traverse, being 2.5 milligal in that one. The last-mentioned traverse was composed of 54 links, had a length of 300 to 350 miles, and for 100 miles was along the Gulf Shore. The other two of the three traverses were composed of 23 links and were each 150 (plus or minus) miles long. It should be noticed that the four other traverses which were 150 or more miles long had errors of closure less than 0.5 milligal.

The probable error of ±0.09 milligal is close to the limit of observation with the present optical system. The scale is read to half-scale divisions, and the coefficient of scale-division is 0.15 to 0.20 milligal.

These observations are not precise in terms of what the instrument can do but are merely routine field-observation made day in and day out by observers, some of whom have no technical training. More precise observations could be made if necessary.

Humble Oil and Refining Company,
    Houston, Texas

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AMERICAN GEOPHYSICAL UNION

Eighteenth Annual Meeting

SECTION OF SEISMOLOGY

Washington, D. C.
April 29, 1937

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CURRENT GEOPHYSICAL ACTIVITY IN TEXAS, LOUISIANA, AND THE MID-CONTINENT

Donald C. Barton

(Abstract)

The extent of the current activity as of April, 1937, in geophysical exploration in Texas, Louisiana, and the mid-continent is given in Table 1.

Table 1--Activity in geophysical exploration, April 1937

State or division	Seismic crews	Torsion-balance crews	Gravimeters	Magnetometers	Electric crews
Indiana	1	..	..	..	..
Illinois	8	..	..	..	..
Colorado	2	..	..	..	..
Kansas	11	..	..	..	..
Oklahoma	24	..	2	..	..
Southern Arkansas	6	..	..	..	..
Northern Louisiana	19	..	..	..	..
East Texas	4	0	0	1	0
West Texas	15	5	2	1	0
New Mexico	0	1	2	0	2
Gulf Coast					
Texas	50	14	7	4	4
Louisiana	34	11	3	1	0
Mississippi	5	2	5	0	0
Totals	179	33	21	7	6

No pendulums are being used as far as I know. Of the electrical crews, at least one-half are experimental. These data are not so accurate for the mid-continent as for Texas and the Gulf Coast. A few magnetometers, torsion-balance crews, and an electrical crew may be working in the mid-continent. The activity in the northern mid-continent presumably will be greater when the summer field-season opens.

Humble Oil and Refining Company,
Houston, Texas

SEISMIC REFRACTION-METHODS AS APPLIED TO SHALLOW SUBSURFACE EXPLORATION

E. R. Shepard

(Abstract)

For determining the presence and location of solid rock-formations, and for classifying soils and other underlying strata with respect to their relative degrees of compaction, the seismic method appears to be more dependable than the electrical resistivity-method and has an inherent advantage over all other methods now used, in that it measures directly the rigidity of the Earth's crust. A highly compact and relatively portable seismograph has been developed which is particularly suited to the shallow exploration required for highway and other construction-projects. A blasting cap or small charge of dynamite exploded at or under the surface of the ground becomes the center of a wave-disturbance. Sensitive microphone-detectors placed at different distances from the shot pick up the disturbance successively and transmit the electric impulses to galvanometers which record them as light-traces on a moving photographic film. By means of an accurate timing-mechanism the time of transit of the wave-disturbance from the shot-point to each detector can be determined from the film, the speed of transit being indicative of the elastic character of the material traversed. Data from a number of shots are plotted on a time-distance curve, and the relative rigidities of the underlying materials thereby classified. The thickness of the surface-layers of soft material over denser layers of clay or shale are indicated, and likewise the depth to material of still greater rigidity, such as rock. The results of tests on a large variety of formations in the District of Columbia and nearby Virginia and on the Pacific Coast have demonstrated the value and practicability of application of this method of exploration to the construction of highways and other engineering structures.

U. S. Bureau of Public Roads,
Washington, D. C.

SEISMOLOGY AND THE GEOLOGICAL EXPLORATION OF OCEAN BASINS

R. M. Field

In terms of description and speculation, the suboceanic lithosphere, or some 70.80 per cent of the area of the Earth, is still a "state of mind rather than a place." This statement is equally true both from the geological and geophysical points of view, even if in the minds of some students of Earth science there still remains a subtle, if not practical, distinction between the relative value and importance of the various theoretical and exploratory methods, and the meager data which they have, as yet, produced. Until quite recently geologists have had to confine their study of the Earth to immergent areas of the continents which, in themselves, constitute only some 29.20 per cent of the surface of the Earth, not including large and important areas covered by ice. Of particular significance have been the stratigraphic and structural studies of the immerged area of the "Atlantic Province," and the effect which these studies have had in the formulation of paleogeographic hypothesis, or the distribution of land and water through geologic time.

The relatively recent development of the science of geophysics, or the application of the principles and methods of experimental physics to the study of the structure and history of the Earth, is slowly but surely having a profound effect on both geological surveying and geological thinking. The remarkably successful record of the economic geophysicists is excellent proof of the value of geophysical methods, especially in extending the depth of geological surveys, but it is only recently that geologists have begun to apply geophysical methods (on the same scale and with the same success) to purely scientific problems. It is an interesting fact that the petroleum geologists have supplied most, if not all, of the standard geophysical techniques for the study of subsurface structure. When, on the other hand, we consider the contributions which the theoretical (mathematical) geophysicists have made to Earth science, we find decided differences of opinion between geologists and geophysicists. It must be remembered that, according to any practical definition, geophysics is a much younger science than geology, and that the training of a geophysicist is fundamentally different from that of a geologist, unless the latter has had at least the elements of an engineering training. This is particularly true in relation to seismology and the structure of oceanic basins.

Any discussion regarding the structure of oceanic basins necessarily has to take into consideration the prevailing theories regarding their origin. It is well known that there are two prevailing theories: One that all oceanic basins have been permanent throughout geologic time; the other that possibly only what remains of the Pacific Basin is original, and that the Atlantic Basin did not begin its existence until the Late Paleozoic. This is the theory of drifting continents or the Wegener hypothesis. It is interesting to note that, both among geologists and geophysicists, there are those who approve and those who disapprove of the Wegener hypothesis. Among the geologists, most paleontologists and stratigraphers disapprove, especially in the United States. This is interesting because the principal object of the hypothesis is to overcome serious paleogeographic difficulties. Among structural geologists, the principal exponents are those who are either particularly familiar with Alpine tectonics or who, for one reason or another, believe that there must have been great lateral translations of large portions of the Earth's crust, even on the order required by the Wegener hypothesis. The majority of the "theoretical" geophysicists believe in the Wegener hypothesis without necessarily having paid any particular attention to the reasons why it was proposed. Probably most seismologists have paid more attention to the phenomena of earthquakes, and the light which they may throw on the zonal structure of the Earth than on any theory as to the origin of continents and oceanic basins, or the present pattern of the face of the Earth. It is, therefore, particularly interesting to refer once again to Gutenberg's and Richter's discussion of the shallow earthquake-waves which traverse the continents and oceanic basins, especially as described under the title of the "Structure of the Earth's crust and the spreading of the continents" (Bull. Geol. Soc. Amer., v. 47, pp. 1587-1610, 1936).

This paper by Gutenberg and Richter is of particular significance because: (1) It provides probably the most important data now available on the relative difference in composition of the basins of the Pacific, Atlantic, and Indian oceans, and the continents; (2) they assume that the data do not entirely disprove the migration of continents, but only modify the mechanics in the form of a new theory which they call the "Fliesstheorie," or the "theory of continental flow," as opposed to the "theory of continental drift." Gutenberg's and Richter's statement ("Although the velocity of elastic waves under the Pacific Ocean at a depth of ten km is the same as in rocks at a depth of 40 to 50 km in the continents, the crust under the Atlantic and the Indian oceans shows elastic properties similar to those found, from seismic as well as geologic data, to be continuous, the transitions from the continents to the Pacific Ocean is abrupt"), is so important in itself, regardless of the "Fliesstheorie," that it deserves further tests, especially in relation to the sub-Atlantic lithosphere.

During a recent conference on the seismic study of oceanic basins, Captain N. H. Heck suggested that, since the middle Atlantic is an "active" region, earthquakes which originate here are of particular interest in relation to the problem (see statement in 1937 report of the Special Committee on Geophysical and Geological Study of Oceanic Basins). Dr. H. Landsberg has called my attention to the following statement in the Seismological Report of the Taunus Observatory, 1932: "Als wesentliches Ergebnis ist ober hervorzuchen, dass die Anordnung der Stationen auf beiden Kurven eine Azimutabhängig keit zeigte. Stationen mit nördlichen und westlichem Azimut (Vorwiegend Bahnen unter Kontinenten) lagen auf der Kurve mit grösseren Laufzeiten, Stationen mit östlichen azimuten (Bahnen unter ozeanen) wiesen gerikgere Loufzeiten auf." In a recent letter Dr. Landsberg further states that: "The focus of the earthquakes studied at that time from latitude 34° south and longitude 57° east are very suitable for the purpose of investigation. Since 1932 about seven more earthquakes have occurred from that locality, offering additional data. Another set of earthquakes has its origin in the middle of the Atlantic. So far as the records available at this station go, there are five quakes in latitude 0° and longitude varying between 18° and 28° west. From this location radiants go to North America, to South America, to Europe, and to South Africa. Even though the seismic stations in South America and South Africa are scarce, there might be enough information available to throw some light on wave-velocities in the Atlantic."

For the present, it would appear that seismic data refute the Wegener hypothesis, and that these same data do not necessarily prove the "Fliesstheorie." In support of this theory, Gutenberg makes the following introductory statement: "It is based upon a study, not of the forces that produce movements in the Earth's crust, but of the effects of these forces. The forces themselves are still far from being clearly understood." There are several methods, other than seismic, by which the "effects of these forces" may be tested, the most important of which is the topographic mapping of significant areas of the sub-Atlantic lithosphere. The most significant facts are that seismic data tend to refute the Wegener hypothesis and that Gutenberg and Richter have made an outstanding contribution to our almost total lack of knowledge of the general lithology of suboceanic areas. It must be remembered, however, that this information is in terms of a "composite" or "average" lithology for very large areas of the Earth's crust, and and it should not be necessarily assumed that there may not be more clearly defined petrographic and structural provinces in the suboceanic lithosphere than in the continental lithosphere. As has been expressed by the writer previously, it is of the utmost importance that we should attempt to follow the known continental structures beyond the continental shelf into the oceanic basins, especially in the North Atlantic. By discovering the continuity or lack of continuity of known continental structures whose type, origin, and geologic date are known, we may hope eventually to settle the primary question as to amount, if any, that the continents have "drifted" or "flowed." Some four years ago, the geophysical, engineering, and marine difficulties associated with any attempt to adapt the "induced" seismic technique of the petroleum geologist to the structural study of even the submerged continental shelf seemed almost insurmountable. Within the past year, however, a good start has been made on the Atlantic continental shelf, and it is not only hoped but expected that this latest of submarine geophysical methods, under the direction of Professor Maurice Ewing, and with the cooperation of the Woods Hole Oceanographic Institution and the Geological Society of America, will eventually play an important part in the solution of a major geologic problem--the origin of continents and oceanic basins.

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PROGRESS-REPORT IN SEISMOLOGY FOR THE UNITED STATES COAST AND GEODETIC SURVEY AND COOPERATING STATIONS

E. W. Eickelberg

Collection of earthquake information--There are two active agencies for the collection of felt reports, the United States Coast and Geodetic Survey and the Jesuit Seismological Association. The former covers the Pacific Coast and Western Mountain Region through a seismological field-party cooperating with Dr. Perry Byerly of the University of California. The other sections of the country are covered by the Jesuit Seismological Association and the Washington Office of the United States Coast and Geodetic Survey, the Jesuit Seismological Association being interested essentially in the Central Mississippi Valley Area. The Survey has developed on the Pacific Coast a system of reporting earthquakes whereby certain individuals report on shocks on their own initiative, but, in addition to this, special canvasses are made in the case of widespread or destructive shocks. Because of the increased personnel available in the San Francisco Office of the Survey, the work incidental to the preparation of abstract reports has been transferred from the Washington Office to the San Francisco Office.

During the past year, activity in the Pacific Coast Region has been below normal, but within the last few months it has been found necessary to canvass areas affected by four large shocks, none of which, however, was of major importance. The Jesuit Seismological Association has undertaken the canvassing of the region affected by the western Ohio earthquakes of March, 1937. Prof. E. H. Sellards of the University of Texas made a personal investigation of the rather wide area in the Texas Panhandle shaken in June, 1936.

Teleseismic work--The new station [see 1 of notes at end of report] at the Montana School of Mines, Butte, Montana, made possible by the loan of a one-component Wood-Anderson instrument by the Seismological Laboratory of the Carnegie Institution of Washington and recording apparatus by the United States Coast and Geodetic Survey, has been in operation since, September, 1936. Prof. George L. Shue is in charge of the station.

Some work has been done toward the establishment of a new station at the University of Idaho. A single-component seismometer and recorder will be loaned to this cooperative station.

Benioff vertical-motion seismographs have been installed at the University of Vermont at Burlington, at the University of Pittsburgh, at the United States Coast and Geodetic Survey station at Tucson, Arizona, and at Williams College, Williamstown, Massachusetts. The seismograms obtained with the short-period galvanometer at Tucson are being sent to Pasadena for analysis of earthquakes which are too feeble to be recorded by ordinary teleseismic instruments. The long-period records are being forwarded to Washington direct with the Wood-Anderson records. It is expected that the short-period records will to some extent improve control in locating the weaker earthquakes in the southwestern part of the country.

At the Columbia, South Carolina, station the old Bosch-Omori recorders have been replaced by later-type, housed-in recorders with special time-marking equipment. The records have shown great improvement.

Installation of the Wenner seismometers at the Massachusetts Institute of Technology station near East Machias, Maine, was improved. The seismometers were practically sealed up so that they would not be affected by the excessive moisture. The pier for the seismometers was also improved. The recorder was equipped with special device for insuring more uniform motion of rotation. This work was done on a cooperative basis with this Bureau.

The Wenner instruments at San Juan Observatory, Puerto Rico, are being improved by construction of moisture-proof covers and the recorders are being remodeled. The work is arranged so that one component may be kept in operation while the other is undergoing repairs.

Tests were made at the Franklin Institute station for improvement of the technique of determination of ground-motion from the seismograms.

The private station of Mrs. M. M. Seeburger at Des Moines, Iowa, has been changed from smoked-paper to photographic recording, increasing greatly the value of the instruments for teleseismic work.

The shaking-table tests made in cooperation with the National Bureau of Standards were completed and the results with four types of seismometers were published.

The publication of teleseismic results in mimeographed form has been continued as heretofore. Eighteen stations are covered by the reports. Thirty-four epicenters were located from telegraphic data obtained in cooperation with Science Service and the Jesuit Seismological Association. There were no outstanding earthquakes during the year.

A Committee on Promotion of Amateur Seismology has been formed in the Eastern Section of the Seismological Society of America [2]. It is hoped that this Committee will act as a clearing-house for many requests regarding the construction, operation, and general information on seismographic equipment intended for use by amateurs.

There have been many personal calls at the United States Coast and Geodetic Survey by individuals interested in the establishment of first-order seismograph-stations, and an attempt has been made to cooperate to the fullest extent in supplying the necessary information.

Recording of earth and building motions in epicentral regions--As a result of the recent seismic activity in the Western Mountain Region, the distribution of instruments for recording strong motions has been greatly extended. New stations [3] have been established as follows: Butte, Montana (Montana School of Mines); Missoula, Montana (University of Montana); Helena, Montana (University of Montana); Bozeman, Montana (Montana State College); Hawthorne, Nevada (United States Naval Ammunition Depot); Boulder City, Nevada (three units, Bureau of Reclamation).

The accelerograph formerly at Balboa, Canal Zone, was transferred to Miraflores, Canal Zone. The accelerograph at Salinas, California, was discontinued pending provision of housing facilities.

An earthquake of intensity VII occurred on July 15, 1936, in northeastern Oregon, south of Walla Walla, Washington. There were no accelerograph-stations close enough to record this shock, but a new station is contemplated for that vicinity.

During the series of aftershocks of the Montana earthquakes of October 1935, it was noticed that for some shocks the ordinary pendulum-starter failed to start the accelerograph. The earth-motions being largely vertical at those times, a vertical-component pendulum was then improvised which answered the purpose temporarily. The four new Montana accelerographs, constructed for the major part by the Instrument Division of the United States Coast and Geodetic Survey, are equipped with drift-compensation vertical starters as well as with the usual pendulum-starters. The three Boulder Dam accelerographs are similarly equipped. The latter were constructed under contract in accordance with specifications prepared by this Bureau for the Bureau of Reclamation. Inspections and tests were made by personnel of this Bureau before acceptance was authorized. Installation is now being made under the supervision of the seismological field-party.

Strong-motion records were obtained during the year for the following earthquakes: May 6, 1936, Miraflores, Canal Zone, intensity IV-V; June 3, 1936, epicenter off coast of northern California west of Humboldt Bay, intensity V; June 11, 1936, epicenter near Helena, Montana, intensity V; June 12, 1936, epicenter near Helena, Montana, intensity V; October 10, 1936, epicenter near Bishop, California, intensity IV; February 6, 1937, northern California, near Ferndale, intensity V; February 19, 1937, Hawthorne, Nevada, intensity IV; March 8, 1937, Berkeley, California, intensity VI-VII; March 25, 1937, Palm Springs, California, intensity VI.

In connection with the earthquake of March 8, 1937, at Berkeley, the tiltmeter-records gave no definite indication of excessive tilt at that time. There are four of these instruments at Berkeley which are being operated in cooperation with the University of California. An automatic recording device was installed on one tiltmeter.

The last strong-motion record obtained in the Helena (Montana) Area was June 12, 1936. Aftershocks are still being felt, although they are mostly weak ones. The record of felt aftershocks is being kept by W. E. Maughan, Associate Meteorologist of the United States Weather Bureau. From October, 1935, to April 30, 1936, there were 1882 aftershocks; from May 1, 1936, to March 31, 1937, there were 461--23 weak shocks having been felt during the month of March.

Leveling for the purpose of detecting earth-movement resulting from earthquakes was run in the vicinity of Helena, Montana, in the early part of last summer.

In the Washington Office a precise analysis by methods of integration was made of a strong-motion record obtained in Montana during the destructive series of shocks in October, 1935. Although development of a torsion-pendulum analyzer has been contemplated, nothing has been done to date to supplement experimental work carried on in the spring of 1936. It is expected that the analyzing of strong-motion records will be greatly facilitated through the construction of a finished machine.

In order to test the accuracy with which the Bureau's strong-motion instruments operate and the accuracy of computations made by integration-methods, a series of tests are contemplated on the new shaking-table of the Department of Civil Engineering of the Massachusetts Institute of Technology. The work will be carried out by personnel from that Institute and this Bureau. One of the most interesting phases of this test will be to check the validity of the long-period waves of large amplitude which have been obtained from the records on hand.

Vibration-work--Vibration-work in buildings, on bridges, and other engineering structures was continued, but not on the scale of previous years. Most of the effort was spent in making analyses and preparing reports on field-work previously done.

The analyses of the comprehensive series of vibration-observations of the Golden Gate and San Francisco Bay bridges at various important stages of construction furnish some interesting data. The observations began on completion of the piers and were repeated from time to time until completion of the structures. A pier on land behaved as a simple inverted pendulum, whereas in the water the vibrations were complicated by the striking of waves and the surge of the water. This effect was still noticeable on the vibration-record after completion of the superstructure.

In a typical case the dominant period of the top of a tower was 3.6 seconds before and 6.7 seconds after addition of the cable. Addition of steel in the span caused a further increase in period to 7.5 seconds. Further construction, decks, etc., served to stiffen the structure until upon completion the period of the tower-top was reduced to 4.5 seconds. Amplitudes were decreased from 15 to 50 per cent of the amplitudes when tower was standing alone. The longest transverse-period at mid-span of the cable after steel work had been extended from both towers was about 22 seconds for the Golden Gate Bridge and 15 seconds for the Bay Bridge. A new field-party was organized to measure ground- and building-periods in southern California in connection with the Veterans Administration Hospital Facilities. This required considerable experimental work both with instruments and methods of shaking the ground. The ground was agitated with a special shaking-machine and by blasts of dynamite. The results obtained to date seem to indicate that dominant ground-periods obtained in this way are in good agreement with the dominant ground-periods observed during strong earthquakes. This is very important from the engineering viewpoint.

A new Benioff vibration-meter and recorder has been purchased for use in ground and building vibration-tests. The instrument is designed for use in making simultaneous records in different parts of a building and is now undergoing intensive tests.

A portable oscillator was designed and constructed at Stanford University under the direction of Professor L. S. Jacobsen. This oscillator is being used very successfully for setting low buildings into vibration in order to determine the periods of vibration.

Publications--The following publications were issued during the year:

"United States earthquakes, 1934" contains statistical information on felt earthquakes in the United States and possessions and results of special strong-motion work.

"Earthquake-investigations in California, 1934-1935" is a 233-page report by various authors, all experts in their fields. The subjects covered include precise measurement of ground- and building-motions resulting from natural and artificial causes including earthquakes, results of a special survey of structural damage at Long Beach, a special study of many seismographic records obtained at Pasadena, and collection of non-instrumental data.

"Selection, installation, and operating of seismographs" was prepared primarily as an aid in the selection of seismographs and station-sites for the recording of distant earthquakes. It contains also descriptions of accelerographs, tiltmeters, vibration-meters, etc.

Mimeographed reports were issued during the year as follows:

"Monthly seismograph-report" is a register of seismogram-interpretations for 18 stations.

"Preliminary determination of epicenter" consists of post-card reports which give preliminary epicenter-locations a few days after the occurrence of strong earthquakes anywhere in the world.

"Abstracts of non-instrumental reports" are quarterly summaries of earthquake-information furnished by cooperators on the Pacific Coast and in the Western Mountain Region.

"The progress-report" is a quarterly statement on the results of special seismological investigations in California and throughout the Western Mountain Region.

"Principles underlying the interpretation of seismograms" is a 37-page discussion of seismic wave-propagation, instrumental response, and seismogram-analysis.

Exhibits--A six-inch accelerograph with a special shaking-table and cabinet of glass and steel has been on exhibit during the recent exposition at Dallas, Texas. This instrument is now on exhibit at the Hayden Planetarium of the American Museum of Natural History in New York, New York. It will be returned to the Dallas Exposition if provision is made for such an exhibit by those in charge of the project.

Notes

[1] A complete list of seismograph-stations in the United States is published in United States Coast and Geodetic Survey Special Publication No. 206 on the "Selection, installation, and operation of seismographs." A similar list appears in Transactions of the American Geophysical Union, 1936, part 1, p. 79.

[2] Rev. James B. Macelwane, S.J., Chairman, Committee on Amateur Seismology, Eastern Section, Seismological Society of America, Director of the Department of Geophysics, St. Louis University, 15 North Grand Boulevard, St. Louis, Missouri.

[3] A complete list of "Strong-motion seismograph-stations" is published in United States Coast and Geodetic Survey Special Publication No. 206, mentioned above.

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A PRELIMINARY REPORT ON THE OHIO EARTHQUAKES OF MARCH 2 AND 9, 1937

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(Abstract)

Both of the shocks of March 2 and 9, 1937, were felt over a wide area, the one of March 9 being notably stronger and reported as felt over an area of more than 100,000 square miles. The original estimate from the Xavier seismograms of an epicentral distance of 90 miles from Cincinnati was confirmed by the field-evidence, which showed the greatest damage at the town of Anna, Ohio, though slight damage was reported from many places. The character of the damage done was described and attention called to the apparently systematic direction of rotation of tombstones in various cemeteries near Anna. On account of the thickness of the overlying glacial till, little is known of the geological structure beyond the general folding associated with the Cincinnati anticline. Well-logs indicate an old, narrow pre-glacial channel as underlying the town of Anna. The flow of artesian wells as well as in oil- and gas-wells in various localities was affected by the shocks. From five observers about ten miles west of the epicenter came reports in regard to the interesting but unexplained phenomenon of a reddish illumination of the sky at the time of the earthquake. This was in connection with the second shock, which took place at 12:45 A.M.

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TIMISKAMING EARTHQUAKE-DATA AND TIME-DISTANCE CURVES FOR DILATATIONAL WAVES

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The Timiskaming Earthquake occurred shortly after 1^h, eastern standard time, November 1, 1935. A preliminary analysis by means of first arrival-times at Ottawa, Buffalo, Shawinigan, Harvard, Chicago, Georgetown, and Saint Louis indicated an epicenter near the town of Timiskaming, Quebec, and a focal depth of 200 km. Subsequent field-work resulted in a slight modification of the coordinates of the epicenter. The following were the values deduced from the combined studies: Latitude of epicenter, 46° 47' north; longitude of epicenter, 79° 04' west; focal time, $6^h\ 03^m\ 40^s$ GMT, November 1, 1935; depth of focus, 200 km. The work, up to and including this deduction, is reported in some detail in a paper entitled "The Timiskaming Earthquake of November 1, 1935: The location of the epicenter and determination of focal depth" (J. Roy. Astr. Soc. Can., v. 30, No. 4, 1936).

Records were received from 61 seismograph-stations. These are now being studied. The present paper outlines the progress made to date. So far, the studies have been confined to the first arrival-times of the P-wave. Readings which may be used for this purpose have been made from the records of 23 stations. The greatest epicentral distance involved is that of Ksara (80° 43'); the least is that of Ottawa (2° 43'). The range is fairly well represented from 2° to 12°. There is no station between 12° and 22°. A group of stations fills in the distance-range fairly well from 30° to 64°. There is a blank from there to 80°. Most of the arrival-times are sharply defined. The time-corrections are given in each case and are apparently dependable.

The P-curves of Jeffreys (1933), Macelwane (1933), Brunner (1935), and Gutenberg (1936), for normal-focus earthquakes, and those of Brunner and of Gutenberg for focal depths of 100 km and 200 km were carefully plotted on section-paper 40 cm by 50 cm. On fitting over these the arrival-times for the 23 stations, plotted to the same scale on tracing paper, it was found: (a) That they seem to agree best with Jeffreys' curve; (b) that they can not be made to fit any curve of much-greater-than-normal focal depth; (c) that the arrival-times for Shawinigan Falls (4° 21') and Seven Falls (5° 38') are definitely early; and (d) that the arrival-time for Bozeman (22° 04') is late.

The results (a) and (b) seemed to contradict the location first obtained on December 1, 1935, on the basis of arrival-times for seven stations. Combined with result (c) they suggested a recalculation of the location, based on the same data and carried out in the same way. This was done and the earlier computations were found to be correct. It was also found that, while the first arrival-times at Shawinigan Falls and Seven Falls are too early to agree with a normal-focus graph, they are essential to a location for 200-km depth for the data from the seven stations first used.

On January 20, 1936, an aftershock was reported by telegraph from Timiskaming. No trace was found on the Milne-Shaw records at Ottawa but the tremors were fairly well marked at Shawinigan Falls on the short-period Wood-Anderson and less well defined on the Wood-Anderson at Seven Falls. Moreover, there were later sharp offsets on the Shawinigan and Seven Falls records for November 1, 1935, which would agree well with the normal-focus graph. It is deduced that there was a fainter foreshock at Timiskaming which was about as intense as the aftershock of January 20 or, perhaps, a little less. This hypothetical foreshock would not record at Ottawa but would account for the earlier emergences at the Quebec stations. Further study of this point is to be made, but it seems safe to assume that this explanation is the true one and to use the second arrival--the sharp impulses--at the Quebec stations in combination with the other data in our present analysis.

We therefore abandoned the earlier deduction of 200-km focal depth and, tentatively, assumed normal focus. This is, moreover, in accord with the appearance of the records from the various stations. It was a fortunate chance which resulted in the location based on the earlier assumption being so nearly correct as to direct the field-work into the proper area.

The late arrival at Bozeman (22° 04') led to a careful revision of that reading, but the record was found to be exceptionally clear and there seems no reason to doubt the time-correction given. The reading is confirmed. A plotting of Jeffreys' P-curve as given in his paper on deep-focus earthquakes (1935, No. 2978 Bib. Seis.) shows a crossing of the curve at 20° due to a discontinuity at a depth of about 440 km. If we were to use these curves, Bozeman would fit almost exactly on the continuation of the first curve beyond 20°. Further study will be made of this result. It has considerable promise.

The first arrival-times for the 23 stations were first fitted by least squares to Jeffreys' curve of 1933 making the following initial assumptions: Latitude (geocentric) of epicenter, 46° 35'; longitude of epicenter, 79° 04'; focal time, $6^h\ 03^m\ 40^s$, GMT; normal focus. The derived corrections and their probable errors are as follows:

$$\delta\varphi_e = -0\overset{\prime}{.}97 \pm 2\overset{\prime}{.}84; \qquad \delta\lambda_e = -0\overset{\prime}{.}39 \pm 6\overset{\prime}{.}06; \qquad \delta H = -0\overset{s}{.}06 \pm 0\overset{s}{.}64$$

Evidently, on the basis of this analysis we are not justified in making any change in our initial assumptions.

In setting up this initial least-squares solution, the suggestion was made by Mr. Stewart that the differential coefficients for the Geiger method be evaluated from the formulae instead of being computed as the ratio of increments. The required analysis was given over to John Hodgson, who has been assisting throughout the research here reported. He prepared a short paper giving the formulae required and showing the magnitude of the errors involved in using the ratios of increments for certain limiting cases (this paper is being published in the April 1937 issue of Bull. Seis. Soc. Amer.). The results are neat, and their application saves considerable labor in working to a prescribed precision.

A similar solution was next carried through using Brunner's normal-focus curve which is practically that of Macelwane but begins at the origin instead of 10° as does the latter. The resulting corrections and probable errors are as follows:

$$\delta\varphi_e = -11\overset{\prime}{.}25 \pm 4\overset{\prime}{.}14; \qquad \delta\lambda_e = -35\overset{\prime}{.}46 \pm 8\overset{\prime}{.}83; \qquad \delta H = +3\overset{s}{.}86 \pm 0\overset{s}{.}96$$

These results conflict with the field-work evidence and are not tenable.

A four-term least-squares solution was next set up with the added term $\partial T/\partial d$, where T is the transmission-time and d is the focal depth (measured positively downwards). The resulting corrections and probable errors are as follows:

$$\delta\varphi_e = -13'.42 \pm 0'.67; \quad \delta\lambda_e = -38'.83 \pm 12'.96; \quad \delta H = +5^s.08 \pm 3^s.49; \quad \delta d = +9 \text{ km} \pm 24.67 \text{ km}$$

These results also conflict with the field-work evidence and are not tenable.

We conclude at this stage that, on the basis of the time-distance curves so far tried, the epicenter as determined by the field-work cannot be improved by the first arrival-times available, the tenable prescribed shifts being less in each case than the probable errors for the one solution which does not conflict with the field-work. There seems no doubt that the focus is not deep as was first supposed. The value of the focal depth and the time at the focus are not yet finally determined.

It is next proposed to check the first arrival-times against Jeffreys' curves as given in his paper "Some deep-focus earthquakes" (Mon. Not., Roy. Astr. Soc., v. 3, 1935). A four-term solution will be made to find the curve which gives the most probable solution for epicenter and focal depth. It is expected that this study and that of the later phases will yield interesting data with regard to the 20° discontinuity of Jeffreys.

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INTENSITIES OF EARTHQUAKE-NOISES

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The sound-phenomena accompanying earthquakes are not yet fully explained as regards their origin. In particular, the question whether they are produced by the felt, or recorded, shock-waves themselves, or are to be regarded as independent waves, has not been satisfactorily answered. The shock-waves recorded at Mt. Tukuba lead W. Innouye [see 1 of references at end of paper] to believe that they might induce sounds. There, with short periodic accelerographs, wave-periods of 0.02 second have been observed, well within sound-frequency. On the other hand, from mapping sound-intensities in epicentral regions, A. Sieberg [2] found that sound-centers were often different from the shock-foci.

The energy of shock-waves passing into the air had already been computed by C. G. Knott [3], who found that only about 0.00013 of the energy of an incoming longitudinal wave passed as sound-energy into the air. From the formulae developed by H. Blut [4] for the distribution of energy at an interface, a very simple derivation can be made in the case of an almost vertical incidence of waves. In an epicentral region with not too shallow focal depth, this condition will be fulfilled, and the ratio between the incident longitudinal energy, E_1 (shock-wave), and the refracted longitudinal energy released into the air, E_r (sound-wave), will be

$$E_1/E_r = (1/4)\ [2 + (v_1\rho_1/v_2\rho_2) \ + (\rho_2 v_2/\rho_1 v_1)]$$

where v_1 and v_2 are the longitudinal wave-velocities in the rock and the air, respectively, and ρ_1 and ρ_2 are the corresponding densities. If one assumes the values $v_1 = 4.5$ km/sec, $v_2 = 0.33$ km/sec, $\rho_1 = 2.7$, and $\rho_2 = 0.0013$, then the last term in the parenthesis will be negligibly small and the energy-ratio will be approximately 7100. This result is in agreement with Knott's value. For general purposes one may therefore say that only about 1/10000 of the shock-energy will transform into sound in the air. The energy of sinusoidal shock-waves, according to B. Gutenberg [5], is

$$E = Ka^2/T^2$$

where K is a constant, a is the amplitude of the wave, and T is its period. Values computed from this formula can be used for comparison with actually observed earthquake-sound intensities. These sounds do not represent simple longitudinal waves of one frequency and a better term for them, therefore, would be "noises." In most cases, they are described as deep rumbling noises which are close to the lower limit of audibility. It may sometimes be hard to distinguish between feeling and hearing of the sound--a phenomenon which is also observed in listening to organ music, when very low notes are used. Then one sometimes seems more to perceive a vibration than to hear a sound. The relations between noises, their intensities, and their effects on the observer, have been very well studied by acoustical engineers and noise-abatement commissions [6].

These experiences can well be used in a study of the problem of earthquake-noises. In noise-measurements, physical energy-units have been replaced by the decibel unit (db) for convenience; as reference-base the intensity at the threshold of hearing is used, equal steps in db corresponding to a logarithmic change in intensity-ratio, as given in Table 1.

Table 1--Intensity-ratios of sounds and decibel equivalents

Intensity-ratio	1	10	10^2	10^3	10^4	10^5	10^6	10^7	.....
No. of decibels	0	10	20	30	40	50	60	70	.....

These decibel steps are not equivalent to loudness as perceived by the human ear. B. G. Churcher [7] gives for a scale of the sensation produced by noises the following relation to the intensities:

$$\ell = d^5 \times 10^{-8}$$

where ℓ is loudness-steps and d is the value of the intensity of a pure tone of 1000 cycles equivalent to the noise in db above the threshold of hearing. For the 1000-cycle tone this lower limit corresponds to a pressure of 0.0002 dyne/cm^2 or an intensity of 10^{-16}watt/cm^2. The upper limit of audibility is about 10^{13} times larger. For tones of low frequency the threshold is considerably above the lowest limit indicated for the 1000-cycle reference-tone and the total range is less. At energies above the upper threshold of hearing the vibrations are directly felt.

In applying this knowledge, it can be shown, for example, that the sound-wave in air produced by a ground-wave of amplitude 100μ and a period of 0.01 second creates a pressure of the order of magnitude of 1 dyne/cm^2. This would correspond to the loudness of distant thunder--a comparison often used by observers of earthquake-noises. If any higher intensities are observed, they must be attributed to waves of higher frequencies, which have not yet been observed instrumentally in earthquake-regions. The lowest perceptible sound produced in air by an earthquake would have to have at least an amplitude of 10μ at a period of 0.01 second. The ensuing pressure would be about 0.1 dyne/cm^2, which corresponds to the noise produced by the rustle of leaves in gentle breeze. The conclusion is warranted, therefore, that only in a limited epicentral area the heard sounds could be a direct consequence of the simultaneously perceived shock-waves. Since microphone-arrangements for direct measurements in earthquake-regions are, to the writer's knowledge, not employed, the comparisons with familiar sounds used by earthquake-noise observers are the only means of gaining further knowledge. C. Davison [8] has compiled a very complete list of various earthquake-noises. J. Knett [9] and A. Sieberg [2] have devised "intensity"-scales for classifying these noises. Both scales have five intensity-steps. It seemed to be desirable to analyze these scales in the light of recent noise-measurements. To each item, therefore, a value in decibels was attributed and the sensation produced evaluated according to the standards of acoustical engineers. The results are shown in Table 2.

Table 2--Intensities of earthquake-noise scales

Step	Knett scale		Sieberg scale		New proposed scale	
	db	Sensation	db	Sensation	db	Sensation
1	10	2	10	2	20	5
2	25	5	50	20	40	12
3	60	30	65	38	60	30
4	90	70	85	62	80	55
5	100	82	100	82	100	82

Knett's scale is difficult to evaluate since his steps are defined entirely in terms of explosions. Sieberg's scale is admirably arranged according to sensations and represents very closely equal sensation-steps. For physical investigations, however, it seems to be more desirable to have a scale arranged according to intensities, in order to be able to make interpretations in terms of energies. In Table 2, therefore, another intensity-distribution is proposed. Some characteristics for such a scale are given below:

Intensity-step I--Like whisper, rustling of paper
Intensity-step II--Like conversation, quiet car moving at low speed, distant machine-gun fire, slight knocking
Intensity-step III--Distant thunder, distant gun-fire, rattle of door or furniture, church bells, distant drums, horse vehicle on good pavement, rumbling inside of slow-moving train, sawing of wood

Intensity-step IV--Heavy thunder, avalanche, noise in slow subway, train in tunnel, heavy fall, gun-fire, water-fall

Intensity-step V--Nearby explosion, quarry-blast, noise in airplane, collapse of building

In using the decibel equivalents of these steps it may be useful to remember that in cities the street-noise is above 60 db and in quiet suburban-areas it is above 20 db. Therefore, a noise heard in either place must exceed these values. Furthermore, it may be argued that in rooms the noise-effect is cut down by walls and windows. If one takes the position, as Sieberg does, that the noise comes from the outside, all values perceived in rooms would have to be increased by about 15 db. It is not entirely obvious, however, why a noise generated by a shock-wave should not have the same intensity inside a house as outside, since the walls would be no obstacle for an elastic wave.

The author is indebted to Dr. W. H. Pielemeier for references to publications on measured sound-intensities.

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ON THE ESTIMATION OF FOCAL DEPTH FROM MACROSEISMIC DATA

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Gassmann's method (Jahresbericht des Schweizerischen Erdbebendiensts, 1925) for determining focal depth from the areas enclosed within the various isoseismal lines, leads (after correcting a misprint in the original paper) to the formula

$$1/3\ (J - j) = \log_{10} \sqrt{1 + (R_j/h)^2} + Mph\ \left(\sqrt{1 + (R_j/h)^2} - 1\right)$$

in which J is the maximum intensity, R_j is the radius of the area enclosed within isoseismal j, h is the depth of the focus below the surface of the ground, p is an empirical absorption-coefficient, and M is the logarithmic modulus $\log_{10} e$. This formula has been tried on the two strong earthquakes at Helena, Montana, on October 18 and 31, 1935. The fit is not good; the exponential variation of the energy with distance appears to be too strong.

Another type of assumption leads to the formula

$$J - j = -s \log_{10} \cos \theta \qquad \theta = \tan^{-1} (R_j/h)$$

In this formula the empirical parameter s should theoretically be between 3 and 6; Gassmann's data on the Wallis Earthquake of April 21, 1924, yield s = 5.35. This value was tried on the Montana Earthquakes and gave fair but not good agreement for the various isoseismals.

U. S. Coast and Geodetic Survey,
Washington, D. C.

A NOTE ON LAND-TILT

John P. Delaney

This brief note is presented as a progress-report on the project of measuring seismographically the very slow land-tilting that has been known to affect the lower lakes region.

Previous papers have reviewed the work of Gilbert, Sherman, Moore, and Gutenberg on this subject, and have discussed also the inherent tilt-sensitivities of certain types of horizontal seismometers and their precision in the measurement of very slow and almost infinitesimal tilting.

The Wiechert seismometer at Buffalo has given evidence for a number of years of a very slow southwesterly tilting, precisely the direction of tilting found by Gilbert on geological evidence and by Moore from the data of the water-gage records on the Great Lakes.

The cumbersome Wiechert could not be relied upon for measurement of this tilting, since it is disturbed every day in the process of changing records. A Wood-Anderson seismometer was acquired and set up for the purpose three years ago. It was orientated northeast-southwest, adjusted to a 12-second period, completely sealed in a celotex cabinet, the only opening for the light-beam being sealed with a lens. This instrument was to be left severely alone and undisturbed for the sole observation of the shift in its zero-line under influence of ground-tilt.

As previously reported, three various types of ground-tilting have been observed: (1) Small and irregular tilts definitely associated with barometric gradients; (2) an annual tilting toward the northeast in winter, toward the southwest in summer; (3) a progressive tilt very slow toward the southwest.

This progressive southwest tilting was measured in the winter of 1935-36 when the average position of the light-spot, measured daily, was found to have shifted several inches from its average position as measured the preceding winter. The shift indicated a tilt of the order of 0.7 second of arc in the course of the year. In April 1936 the light-spot left the drum under influence of the annual southwest tilt, but its return was looked for with a view to further measurement in the winter of 1936-37. In the course of the winter the beam did not once reappear. Continuity of measurement is thus broken, but the objective reality of the southwest tilt is forcibly confirmed.

Further investigation will require departure from the proposal of leaving the instrument absolutely untouched, since it will have to be readjusted--better perhaps with a shorter period. The Wood-Anderson seismometer is so small and light that continuity of tilt-measurement would be uncertain under continuous adjustment. The full effect of resetting the zero-position can not be known exactly in terms of second-of-arc tilt. Present plans call for the resetting of the seismometer and for its recalibration with a shorter period, with provision for its continuous use also for earthquake recording.

At the time of the recent Ohio earthquakes both the Wiechert records and the readings of three sensitive spirit-levels were carefully examined for evidence of sudden land-tilting, but no such evidence was found.

Canisius College,
Buffalo, New York

A LOW-COST SEISMOGRAPH AND RECORDING DRUM

H. Rutherford and R. L. Alkire

The science of seismology is one which has been cultivated, for the most part, by professional seismologists. There are amateur astronomers and amateur radio operators. The work of these amateurs has been of great value, not only to the sciences themselves, but also to the cultural advancement of the amateurs. This being true, it would be advantageous to the science of seismology to encourage work by amateurs in this field.

The authors have designed and built a low-cost seismograph and recording drum in answer to the many requests for information regarding such instruments. The total cost of the seismograph and recording drum did not exceed $10. Photographic recording was used because of its many advantages. Smoked-paper recording was not considered since the cost of sensitized paper for this unit will not exceed $0.50 monthly.

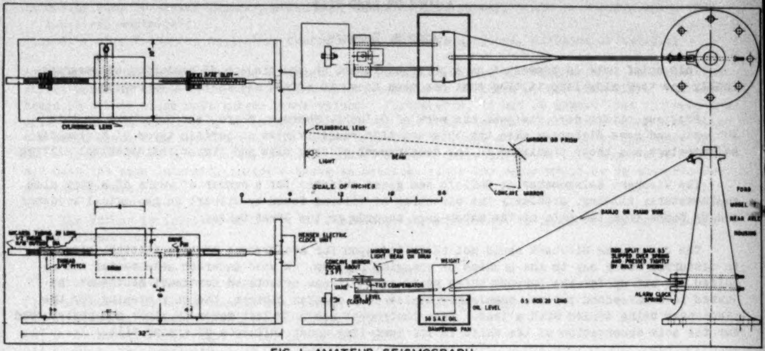
3/32" SLOT
CYLINDRICAL LENS
CYLINDRICAL LENS
LIGHT
BEAM
MIRROR OR PRISM
CONCAVE MIRROR
SCALE OF INCHES
0
6
12
18
24
FORD
MODEL "T"
REAR AXLE
HOUSING
BANJO OR PIANO WIRE
MICARTA TUBING 20 LONG
1/2 INSIDE DIA
5/8 OUTSIDE DIA
THREAD 3/16 PITCH
DRUM
DRIVE PIN
WARREN ELECTRIC CLOCK UNIT
MIRROR FOR DIRECTING LIGHT BEAM ON DRUM
CONCAVE MIRROR FOCUS ABOUT 2.5 FT
VANE
TILT COMPENSATOR
OIL LEVEL (CASTOR)
WEIGHT
OIL LEVEL
30 S.A.E. OIL
DAMPENING PAN
0.5 ROD 20 LONG
ROD SPLIT BACK 0.5" SLIPPED OVER SPRING AND PRESSED TIGHTLY BY BOLT AS SHOWN
ALARM CLOCK SPRING
32"

FIG. 1—AMATEUR SEISMOGRAPH
[NOTE: WITH GOOD OPTICAL SYSTEM PITCH OF SCREW CAN BE REDUCED TO 3/32"]

The drawings of Figure 1 show the essentials of construction for both the seismograph and drum. For the pendulum-support a Ford rear-axle housing was obtained from a junk-yard for $0.50. The pendulum was made from materials found in the shop. The dampening-oil container is an ordinary cake-pan from Woolworth's. Magnification is obtained by a vane suspended in castor-oil as in the McComb-Romberg seismometer. For the mirror-axis two brass pins were soldered on a piece of copper wire. Instead of a prism, an ordinary mirror was used. Wood served as the material for other parts of the seismometer.

In the recording mechanism, micarta tubing of 6-inch diameter was used for the drum. This was mounted on a smaller micarta tubing which was threaded on one end with a 3/16-inch pitch. The opposite end was slit through for about seven inches to take care of the driving pin. The drum is driven by a shaft which is inserted in the micarta tubing. A pin passes through the slit and is fastened to the driving shaft which in turn is connected to a synchronous clock-movement. The bearings are of bakelite, one threaded to take the screw. The micarta tubing cost $3.26 and the motor cost $2.29. The drive-shaft was turned down from a broom handle.

Seismograph Station,
University of Pittsburgh,
Pittsburgh, Pa.

THE TORSION-PENDULUM ANALYSER AS A DOUBLE INTEGRATOR

Frank Neumann

The torsion-pendulum analyser was described in 1936 before a joint meeting of the Section of Seismology of the American Geophysical Union and the Eastern Section of the Seismological Society of America. The purpose of the machine is to compute mechanically the motion of simple oscillators when known accelerations are applied to their supports. More specifically, its purpose is to compute the motion of a pendulum when accelerations, which are obtained from an accelerograph-record during an earthquake, are applied to its support. The same method can be used to compute the motion of a building or other engineering structure. In practice this is done manually by slowing up all of the motions 100 or 200 times. The earthquake-effects are thus reproduced in slow motion.

It is well known that a long-period seismograph-pendulum can be used to measure true displacements provided the periods of the ground-motions are less than about one-half the pendulum-period, and provided there is proper damping. Seismographs of this kind are sometimes specifically called displacement-meters. It follows from this that if the torsion-pendulum of the analyser can be made to simulate the motion of a long-period seismograph-pendulum, it is actually double-integrating the accelerograph-record, that is, converting the acceleration-record directly to a displacement-record for all of the shorter-period waves.

Unfortunately this double-integrating process is restricted to oscillatory motion within a limited frequency-range. How can this limitation be overcome? The first thought is to use a pendulum of extremely long period. This, however, is not practical. The following is a suggested solution which first of all calls for a torsion-pendulum of reasonably long period. Instead of applying acceleration to the pendulum-mass by twisting the torsion-head as in the present experimental apparatus, it is applied to the mass itself in the form of a varying field of force. This may be done by using a variable magnetic field to act on magnets which are fixed to the mass, or the mass itself may be a magnet. The torsion-pendulum thus may take on the aspect of a galvanometer. There then remains the problem of the effect of the suspension-wire on the mass, or magnet, and this must be eliminated before the ideal infinitely long-period pendulum-response is obtained. It appears that the practical equivalent of this can be obtained by turning the torsion-head of the system (either manually or automatically) through the same angular displacements which the pendulum-mass undergoes as a result of the reaction of the pendulum-magnets to the controlled magnetic field which serves as the varying field or force of acceleration. This eliminates the tendency of the mass to return to its original zero-position because no twist is allowed to remain in the wire-suspension. It is believed that such a scheme would be practical in the case of a manually operated torsion-pendulum provided the motions were slow or reasonably uniform.

With such an apparatus, it is believed that conversion of acceleration into displacement could be made practicable not only for oscillatory motions but for any type of motion. One might, for instance, conceive of an apparatus working on this principle which would measure the instantaneous elevation of an aeroplane, being actuated by a vertical-motion accelerometer installed in the ship.

In this solution it may appear at first thought that the introduction of a variable field of force to simulate continuous changes in acceleration is superfluous and that acceleration might still be applied by twisting the torsion-head as in the original experimental pendulum. For long periods, however, the torsion-pendulum functions as an accelerometer and there is but little relative motion between the torsion-head and the pendulum-mass. The extreme case is that of a sustained constant velocity in which acceleration is zero and there is no motion at all of the torsion-pendulum mass. If, however, the acceleration is applied from an extraneous source, the response of the pendulum corresponds to that of any other mass subjected to a variable field of force. A ball rolling on a plane surface which is subjected to variable tilts is a crude example of this type of response except that there is no force acting to restrain the motion of the ball except friction. In such an apparatus the displacement of the ball is the double integral of the curve which represents the instantaneous values of the effective acceleration of gravity--this latter element, of course, varying with the angles of tilt.

In considering the torsion-pendulum as a double integrator for all types of motion it is this latter picture which must be kept in mind rather than the picture of a long-period seismograph which can act in that capacity only to a limited degree.

U. S. Coast and Geodetic Survey,
Washington, D. C.

A NEW THEORY OF THE EARTH'S CORE

Joseph Lynch

The nature of the Earth's interior has long been a puzzle. How hot is it? At what pressure is its center? Is it solid or liquid? Its density as a whole seems to have been well established by Boys and others to be about 5.5. Good figures for the crustal density seem to be about 2.7. We are thus forced to the conclusion that the density increases with depth. Jeffreys postulates 12 for the core-density.

That a core exists is proved quite conclusively by seismology. Reflections from and refractions at a discontinuity about half way down towards the center of the Earth seem quite well established. The velocity of earthquake-waves, both compressional and shear, seems to increase steadily and sharply down to the core whence the velocity becomes more or less constant until the waves emerge from the other side.

Beginning then half way down in the Earth we have this comparatively dense core, but is it solid, liquid, or gas? How rigid is it? Tidal phenomena, the Eulerian period, and seismic phenomena all postulate a core less rigid than the crust. For perfect rigidity an Eulerian period of about 306 days would be required. For zero-rigidity a period of infinity would be needed, whereas the period observed from changes of latitude is 427 days. To comply with the data of tidal phenomena and the Eulerian period a liquid core was suggested and is still quite generally held outside of seismological circles. In the shear-wave of earthquakes, seismology offered a tool with which the rigidity of the Earth could be readily probed. At first it seemed that the shear-wave did not penetrate the core and this was taken to confirm the view already held that the core possessed zero-rigidity or was a fluid. However, four or five seismic investigators in various countries, after careful independent study of different quakes, have come to the conclusion that the shear-wave does pass through the core. Hence it seems that we are faced with the alternatives: (1) The core is a liquid but a liquid under conditions existing at the center of the Earth can transmit a shear-wave; (2) the core is a solid but a solid of much less rigidity than the crust. The present paper dares to add a third possibility, that the core is neither liquid nor solid, but a solid solution--a metal heavily occluded with a gas. Perhaps the suggestion is fantastic, but it was considered sufficiently worth while to determine what effect, if any, such an occluded gas would have on the rigidity of a metal. Palladium was selected as the metal because of the ease with which it could be occluded with hydrogen. A torsion-pendulum, consisting of a half-millimeter palladium wire as suspension and a small magnetized steel needle as the mass, was set up in an alternating-current field. The period was determined by resonance which was found to be extremely sharp. The results show a very definite effect produced on the rigidity of the palladium, a decrease varying from one-tenth to one-fifth of the coefficient of rigidity. The variation in length of the pendulum amounted to about one cm in a seven-cm length of wire. The results have been quite erratic but always showing a decrease in rigidity. The experiment is being continued with the hope of obtaining a curve showing the relation between change of rigidity produced and amount of gas occluded.

It must be emphasized that no attempt has as yet been made to look for and answer the probable objections to such a metallic sponge for the Earth's core, but it was deemed worth while to look into the effect of occlusion on the elastic properties of a metal and the purpose of this paper was simply to state that apparently the coefficient of rigidity of palladium is reduced by an amount of the order of one-tenth or two-tenths when occluded with hydrogen up to several hundred times its volume. Further results will be published later.

Fordham University,
New York, New York

AMERICAN GEOPHYSICAL UNION

Eighteenth Annual Meeting

SECTION OF METEOROLOGY

Washington, D. C.
April 29, 1937

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REPORT ON THE SESSIONS OF THE METEOROLOGICAL ASSOCIATION OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS HELD AT EDINBURGH, SEPTEMBER 17-26, 1936

R. Hanson Weightman

About 50 delegates, representing 15 countries, were in attendance. The contacts between delegates from the different countries were most stimulating and helpful, and a great deal of benefit was derived thereby.

The basic theme adopted for the Edinburgh Meeting was "The problem of atmospheric disturbances," which quite naturally resolved itself into six different divisions, as follows: (a) The definition of a disturbance; (b) origin of disturbances; (c) structure of cyclones; (d) interaction between different layers of the atmosphere; (e) radiation and its role in atmospheric disturbances; and (e) precipitation. A number of instructive papers were read under these six heads and, in addition, there were about a dozen papers of a miscellaneous nature. All were interesting and many evoked discussion.

A special committee recommended that the members of the mixed committee for the study of interactions between the atmosphere and the ocean be composed of Messrs. Sverdrup, Tait, Wüst, H. Mosby, W. Schmidt, and Iselin. To these the names of Messrs. Rossby and J. Bjerknes were added later.

A new committee was appointed for the study of a climatological atlas of the world, such committee to consist of Messrs. Hesselberg (Chairman), Gorczynski (Secretary), Kincer, W. Schmidt, Wehrle, Geiger, and Braak.

The Solar Radiation Committee, the Committee on Ozone, and the mixed Committee on the Polar Year were reappointed.

Congratulatory telegrams were sent to Sir Napier Shaw and W. Koppen.

Minor changes were made in the Statutes of the Association, regarding the election of the President and the Executive Committee.

The resolution tentatively adopted at the reunion jointly of representatives of the associations of Hydrology, Meteorology, Volcanology, and Seismology was approved. In substance this resolution urged an oceanographic network of aerological soundings in the North Atlantic, the placing of an anchored ship in about latitude 55° north and longitude 30° west for the purpose of taking and collecting meteorological observations, and the securing of complete aerological soundings from Iceland and the Azores.

The following officers of the Association were unanimously elected:

President: Prof. S. Chapman (Imperial College of Science and Technology, South Kensington, London, S.W. 7, England)
Vice-Presidents: Dr. P. Wehrle (Director, National Meteorological Office, 196 rue de l'Université, Paris (7), France); W. R. Gregg (Chief, U. S. Weather Bureau, Washington, D. C.)
Secretary: Dr. J. Bjerknes (Geophysical Institute, Bergen, Norway)
Executive Committee: Dr. Van Everdingen; Dr. Hanzlik; M. Mercanton

Most of the papers, resolutions, etc., were either in printed or duplicated form. Having them available in some duplicated form made them more interesting and understandable from a textual as well as from a language point of view, and thereby saved a great many questions.

The gathering as a whole was very impressive, especially in view of the fact that so many men of international reputation were in attendance. It is the unanimous opinion of the American delegates that the meeting was a great success.

U. S. Weather Bureau,
Washington, D. C.

ABSORPTION OF RADIATION BY WATER-VAPOR AS DETERMINED BY HETTNER AND BY WEBER AND RANDALL

H. Wexler

(Abstract)

The two atmospheric absorption-models presented in a previous paper (Mon. Weath. Rev., v. 64, p. 122, 1936) are examined further by comparing them with additional data, namely: (1) Actual measurements of outgoing radiation as observed by Olsson at Spitsbergen and by the United States Weather Bureau in Alaska; (2) magnitudes of ground-inversions found from airplane soundings in Alaska during the winter of 1936-37.

These observations show that the model based on Weber and Randall's absorption-coefficients represents atmospheric absorption of long-wave radiation much better than that based on Hettner's measurements, although, from other considerations, neither seems to be satisfactory under conditions of low temperature and pressure.

This paper is published in the March 1937 issue of the Monthly Weather Review.

U. S. Weather Bureau,
Washington, D. C.

SOME OUTGOING-RADIATION AND SURFACE-TEMPERATURE MEASUREMENTS AT FARGO, NORTH DAKOTA

J. C. Ballard

During the six-months' period ending March 15, 1937, the United States Weather Bureau conducted a program of observations designed to furnish data necessary for a study of cooling of the lower atmosphere. These observations included two airplane flights daily, when weather permitted, at Fairbanks, Alaska, and radiation-measurements at Fairbanks and at Fargo, North Dakota. The project was financed by an allotment from the Bankhead-Jones Research Fund. It is expected that the data collected will furnish, among other things, an observational basis for testing certain theoretical results obtained by H. Wexler of the United States Weather Bureau regarding the process of cooling by radiation which occurs in the lower atmosphere. It is also expected that the value of the work done by the Weather Bureau will be greatly enhanced by similar observations made by the Canadian Meteorological Service at Fort Smith, Canada.

At Fargo, the only additional work involved beyond that ordinarily done at an airport station making airplane observations was the measurement of night-radiation. Measurements were made with the melikeron, which is especially designed for use in measuring the difference between ground- and sky-radiation at night. Measurements were made approximately hourly all night whenever possible and a special effort was made to make them at the time of the airplane observation if they could not be made all night. Unfortunately, Fargo weather on the average is not very favorable for using the melikeron, so that it was possible to make measurements only a relatively small percentage of the time. The melikeron cannot be used during periods of precipitation, while dew or frost are forming, or in blowing snow. Rapid temperature-fluctuations or changes prevent the instrument from reaching temperature-equilibrium and make it impossible to obtain good results. It was found that some results could be obtained when the wind was fairly strong and steady or when it was calm or nearly so, while with light winds and imperfect mixing of the surface cold air and the overlying warm air it was usually impossible to get any results.

Since it will be some time before a thorough study of these observations will be published, it is desired, at this time, to present a few notes of interest regarding the exchange of radiation between the ground- and cloud-layers.

It is very well known that clouds at night retard the fall of the surface-temperature, and that, other things being equal, the temperature will not fall as low on a cloudy night as on a clear one. It is not so generally recognized, however, that the surface-temperature may actually be raised by heat received from warm clouds. The sensitivity of the surface-temperature to cloud-layers had been frequently observed at Fargo, as it probably has at other northern stations. The effect is especially apparent from observations of the temperature-record on cold nights with intermittent cloudiness. A small patch of lower clouds covering only one-tenth or two-tenths of the sky passing directly overhead not only causes the temperature to stop falling

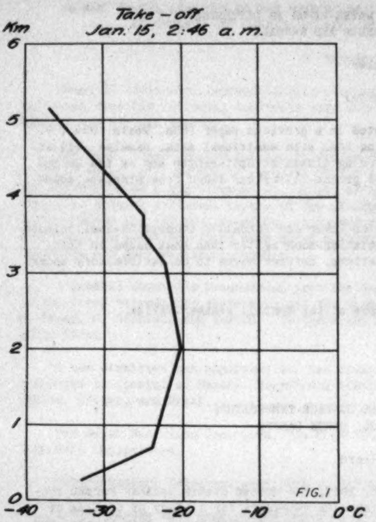

FIG. 1

Fargo, N.D., Jan. 14-15, 1937

Time	T_S	T_M	I	Wind	Clouds
9 pm.	-28.9	-28.3	0.061	N-10	0
10 "	-29.5	-28.7	.056	N-7	0
11 "	-30.6	-30.4	.066	N-7	0
12 "	-30.8	-30.7	.061	N-8	0
3 a.m.	-32.2	-31.7	.039	Calm	0
3:45 "	-32.9	-31.9	.047	Calm	0

but often causes rises of 1° or 2° F. It was not until the past winter, however, that radiation-observations were made and it could be positively shown that during some of these temperature-rises the ground was gaining energy in its exchange with the sky.

Three figures have been prepared. Figure 1 shows a typical case of falling surface-temperature with clear skies, light winds, and a constant loss of heat by radiation to the sky. Figure 2 shows a typical example of what happens when clouds move in. Figure 3 shows an unusual temperature-record in clouds, which was probably produced by loss of heat by the cloud to the colder ground. The "ground," in all cases, is a snow-covered surface. A net excess of outgoing radiation is considered to be positive while an excess of incoming over outgoing radiation is taken to be negative. In Figures 1 and 2, T_S indicates the snow-surface temperature, T_M indicates the temperature in the vicinity of the melikeron (mounted about 25 feet above the ground), and I denotes the net rate of exchange of radiation between melikeron and sky. In Figure 3, T indicates the temperature in a standard instrument-shelter about five feet above the snow. Temperatures are given in the Centigrade scale, wind-velocity in miles per hour, and rate of radiation in gram-calories per square cm of surface per minute.

The data shown in Figure 1 were obtained during the night of January 14-15, 1937. The most important points to note here and to keep in mind are: (1) The sky was clear; (2) the airplane flight showed higher temperatures aloft than at the surface--a total inversion of 12°5; (3) the temperature fell during the entire period; (4) measurements showed a large rate of loss of radiation by the ground. These

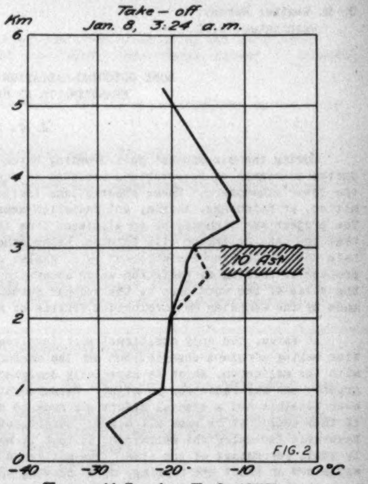

FIG. 2

Fargo, N.D., Jan. 7-8, 1937

Time	T_S	T_M	I	Wind	Clouds
7:30 p.m.	-30	-29	0.039	NNW-16	1 Ast, W
8:30 "	-31	-29	.039	N-15	0
9:30 "	-32	-30	.025	N-16	2 Acu
10:00 "	-32	-30	-.014	N-16	2 Acu +
10:30 "	-29	-29	.006	N-20	3 Acu ++
12:30 a.m.	-29	-29	-.004 to +.004	N-18	7 Ast
1:45 "	-28	-28	.000	N-17	10 Ast
2:45 "	-29	-28	.002	N-15	7 Ast
3:30 "	-28	-27	.002	N-16	10 Ast
4:00 "	-27	-27	-.005	N-18	10 Ast
4:30 "	-27	-27	-.005	N-16	10 Ast

+ overhead ++ few overhead

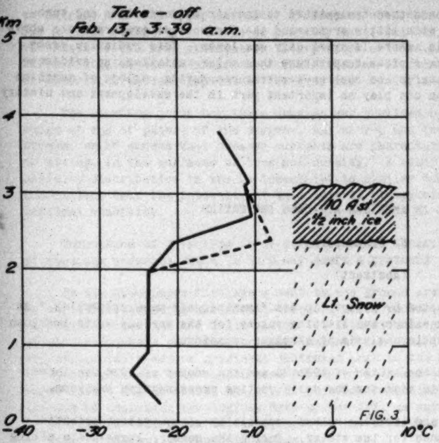

FIG. 3

Fargo, N.D., Feb. 12-13, 1936

Time	T.	Wind	Clouds	Weather
6:45 p.m.	-28.3	NNE-10	7 Ast	Lt. Snow
7:45 "	-27.2	NNE-10	10 Ast	" "
9:45 "	-26.7	NE-7	" "	" "
11:45 "	-25.6	ENE-5	" "	" "
1:45 a.m.	-23.9	NE-9	" "	" "
3:45 "	-22.5	E-13	" "	" "
6:45 "	-22.2	E-8	" "	" "

Total snowfall = 1 inch

data indicate that warm air alone is not sufficient to keep the surface-temperature from falling.

Figure 2 shows typical data obtained as clouds move in. Note that a good wind was blowing from the north throughout the night. The surface-temperature which was falling in the early evening became stationary as the clouds moved in and then rose 5° between 10 p.m. and 4:30 a.m. Radiation-measurements showed comparatively small differences between the energy given out and that received from the sky after the clouds moved in. Some negative readings were obtained, however, which indicate an excess of incoming radiation. It should be pointed out here that the effect of such a strong wind on the melikeron is to reduce the magnitude of the readings obtained, positive or negative, and to tend to make the instrument read zero. The airplane flight, in this case, showed the layer of AST-clouds to be about 400 meters thick and to be about 9° warmer than the ground, as indicated by the solid line. As will be noted, the temperature increased slowly with height in the lower part of the cloud and then more rapidly to the top where a much steeper inversion began. The existence of such a lapse-rate within the cloud-layer means, of course, that no convection could be occurring to produce or maintain the cloud. A plausible explanation of such a lapse-rate is one based on radiation and suggested by Mr. Wexler. Suppose the temperature-distribution at the time the cloud formed were something like that indicated by the dashed line. The lower part of the cloud would then be cooled by radiation to the ground at a more rapid rate than the middle so that the temperature of the whole layer would finally become that shown by the airplane observation. Actually, the temperature of the whole layer may have been considerably higher at the beginning, since the top of the cloud would cool by radiation to space and thus tend to increase the inversion above it.

What appears to be a more pronounced example of this process is shown in Figure 3. No radiation-observations were made at the time of this airplane observation, of course, but the large rise in surface-temperature during the night with northerly and easterly winds should be noted. The temperature-record in the cloud is especially notable, the base of the cloud being at the top of a moderate inversion and the temperature rising another 10° within the lower 300 meters or so of the cloud-layer. A plausible distribution of the temperature at some previous time is likewise indicated in this case by the dashed line. It will be noted that in this case the inversion at the top of the cloud is small. It may be that another cloud-layer above the maximum altitude reached by the airplane retarded cooling of the top of this AST-layer. Unfortunately, no observation of the sky above the AST-layer was made. The base, however, could easily have cooled 12° or so by radiation, causing the precipitation observed. It may be true that the cloud-layer started out much thinner and with the base at a higher altitude, say about 2700 meters, and then built downward by cooling at the base by radiation and the cooling of the air just below it by turbulence, in much the same manner in which ground-fog often builds upward.

At any rate, the points it is desired to stress are as follows: (1) Warm, clear air aloft does not prevent the surface-temperature from falling. (2) Warm clouds not only retard surface-cooling but at times actually cause the surface-temperature to rise. That radiation from the clouds is absorbed at the snow-surface and then transmitted to the air by conduction and turbulence is evidenced by observation that with little or no wind the surface-temperature rises above the air-temperature when clouds moved in, where it previously was lower. This radiation seems to be more effective in raising the snow surface-temperature than solar radiation, as evidenced by observations of snow surface-temperatures and shelter-temperatures during periods of sunshine and during cloudy nights. (3) Radiation can play an important part in the development and history of a cloud.

U. S. Weather Bureau Airport Station,
Arlington, Virginia

FURTHER STUDIES IN AMERICAN AIR-MASS PROPERTIES

A. K. Showalter

(Abstract)

Using the basic classification adopted by Willett in his "American air-mass properties," an attempt is being made to establish mean values and limiting values for the various North American air-masses, as determined from the synoptic analysis of airplane soundings.

The study to date has covered only the winter of 1935-36 and the summer of 1936 for those stations which have reported regularly in time for the daily routine cross-section analyses.

Results indicate that mean values and limiting values, especially of equivalent potential temperature, have a practical significance for the winter. During the summer, large-scale mixing and rapid modification of all air-masses over the Continent tend to produce overlapping of the observed values for the characteristic properties of the different air-masses.

The study is being continued for all seasons, and results to date seem to indicate the desirability of reducing the number of air-mass designations.

[The complete text of this communication will be published later by the United States Weather Bureau.]

U. S. Weather Bureau,
Washington, D. C.

AEROLOGICAL EVIDENCE OF LARGE-SCALE MIXING IN THE ATMOSPHERE

C.-G. Rossby and Collaborators+

As a result of the general acceptance of air-mass analysis by American meteorologists, the number of aerological stations in the United States has been increased to such an extent that it is now frequently possible to prepare daily synoptic charts, not only for the sea-level but also for selected levels in the lower half of the troposphere. At present, this aerological material is being utilized primarily for the purpose of verifying the surface-map analyses, minor exceptions being the use of thermodynamic diagrams in the forecasting of thunder-storms and of ice-formation on aircraft.

Our experience during the last few years indicates that two practically identical surface-maps may be associated with widely different vertical structures; it should therefore be possible

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[+] This communication should be regarded as a preliminary report on a broad investigation in which a number of men participate. The individual contributions are:
(1) Formulation of program--C.-G. Rossby
(2) Synoptic investigation of flow-patterns in selected cases--D. P. Kelly and J. W. W. Osmun
(3) Theoretical investigation of the effect of lateral mixing on atmospheric currents--J. Holmboe and C.-G. Rossby
(4) Model-experiments for the study of wake-stream phenomena in rotating systems--A. F. Spilhaus
Dr. H. C. Willett and J. Namias have contributed generously with suggestions. The ideas set forth in the present communication will shortly be given a thorough test under their direction in connection with the routine-map analyses at the Massachusetts Institute of Technology.

to extract from the upper-air data information not implicitly contained in the surface-reports. Our present inability to do so is probably the result of unsatisfactory methods of representing the state of the free atmosphere. The purpose of this preliminary report is to discuss briefly certain studies now in progress at the Massachusetts Institute of Technology, which have as one of their aims the development of improved methods for the treatment of aerological data.

The starting point for these studies was provided by a recent investigation [see 1 of references at end of paper] of the oxygen-, salinity-, and temperature-distributions in the Gulf Stream, which showed that oceanic currents are characterized by intense, large-scale eddy-motions, or mixing, in the surfaces of constant density. A study by Parr [2] of the temperature- and salinity-distribution in the Caribbean led to similar conclusions. Parr furthermore found some indications that the intensity of this lateral (isopycnic) mixing increases with increasing vertical stability.

Turbulence of this type is of great interest dynamically, since it must give rise to lateral shearing stresses which in turn may exert a profound influence on the current-pattern.

In the atmosphere the layers next to the ground are constantly moving in such a fashion as to obliterate existing horizontal-pressure differences. The rate of this pressure-equalization is easily determined and quite rapid. It follows that somewhere in the middle or upper portions of the troposphere compensating wind-components normal to the isobars must be at work, restoring the horizontal-pressure gradients destroyed next to the ground. It is not inconceivable that these non-gradient wind-components--for which no adequate explanation has been suggested--to a large extent may be caused by lateral stresses resulting from horizontal mixing. Our present methods of analyzing aerological data do not tell us anything about the regions of convergence or divergence thus produced, in spite of their obvious significance for the understanding of the pressure-distribution and its changes.

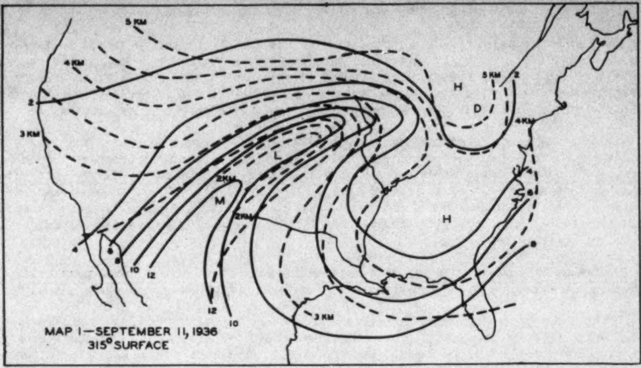
Under ordinary stable conditions any portion of air displaced normal to the potential temperature-surfaces will be subjected to a stabilizing force whose magnitude is proportional to the potential temperature-gradient. There is no such restraint on displacements parallel to the surfaces of constant potential-temperature. Thus there is reason to believe that lateral mixing in the atmosphere must be confined to surfaces of constant potential-temperature. In case of saturated air, mixing will presumably follow surfaces of constant equivalent potential-temperature. Since vertical mixing is never completely absent and since it necessarily must exert a restraining influence on the displacement of large eddies along the isentropic surfaces, one may apply Parr's principle and surmise that horizontal mixing reaches its maximum where the vertical gradient of potential temperature has its maximum value, that is, in fronts and inversions. Furthermore, since the lowest 500-1000 meters are characterized by nearly adiabatic lapse-rates and strong vertical mixing due to ground-friction, one should expect that horizontal mixing here reaches a minimum, apart from forced horizontal eddy-movements resulting from irregularities in the terrain.

By definition, a frontal surface separates air-masses of dissimilar characteristics. Unless it be assumed that there is a rapid exchange of properties across the front, it follows that the latter must coincide with a surface of constant potential-temperature, or, in case of saturation, with a surface of constant equivalent potential-temperature. This does not exclude the possibility that transient kinematic discontinuities of different orientation may occur.

The preceding comments contain both the nucleus of a working hypothesis concerning the nature of atmospheric currents and a suggestion as to the proper method for their representation. We have attempted to investigate the tentative deductions set forth above with the aid of aerological data for selected synoptic situations. In view of the isentropic character of the lateral mixing process it was decided to study the distribution of specific humidity in individual surfaces of constant potential-temperature, in the same way as the advection and lateral mixing of oceanic currents may be investigated by studying the oxygen-distribution in isopycnic surfaces. The charts thus obtained are similar to the isentropic weather-maps suggested some years ago by Shaw [3].

Since at higher levels also the mean motion must be very nearly adiabatic, it follows that the air in a given isentropic surface must be the same from day to day. A comparison of the observed changes in the specific humidity distribution from one chart to the next with the purely advective change to be expected from the observed wind-distribution should therefore give some indication of the rate of mixing.

In the lowest layers the moisture-distribution is very largely controlled by convection and vertical mixing, while at high levels the variations in specific humidity are too small and the


5 KM
4 KM
3 KM
2
H
D
5 KM
2
4 KM
L
2 KM
M
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H
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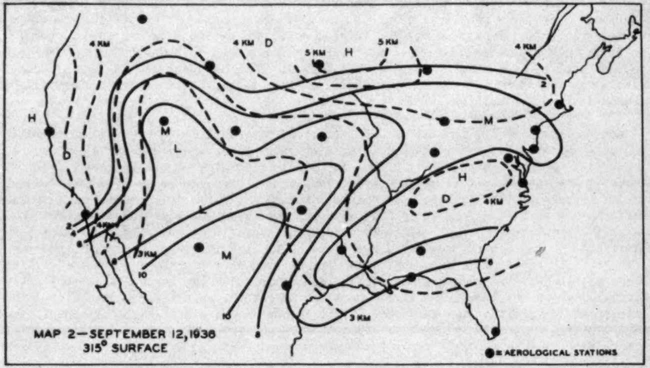
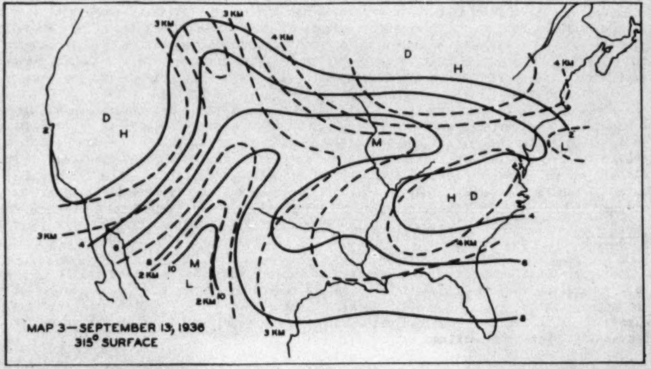
6
8
10
12
12
10
3 KM
6
8

MAP 1—SEPTEMBER 11, 1936
315° SURFACE


4 KM
4 KM
D
5 KM
H
5 KM
4 KM
H
D
M
L
M
H
D
4 KM
2
4 KM
2
4
6
6
3 KM
10
M
10
8
3 KM
4
6
● = AEROLOGICAL STATIONS

MAP 2—SEPTEMBER 12, 1936
315° SURFACE


3 KM
3 KM
4 KM
D
H
4 KM
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H
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M
2
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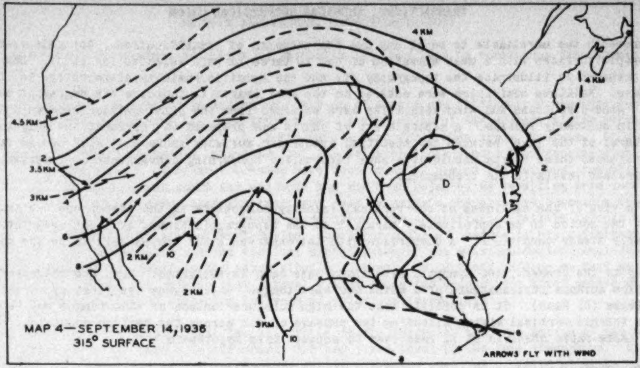
H
D
4
3 KM
4
6
8
2 KM
10
M
L
2 KM
10
4 KM
6
3 KM
8

MAP 3—SEPTEMBER 13, 1936
315° SURFACE

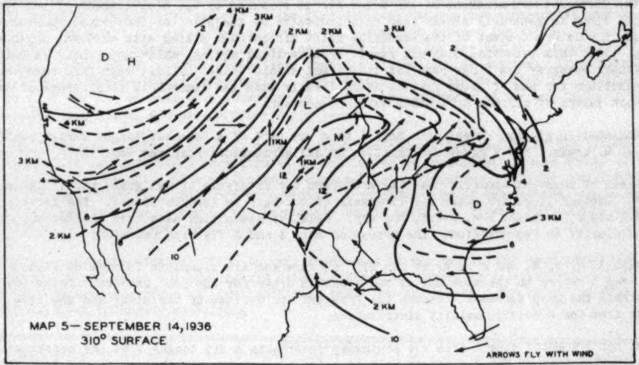
GENERAL LEGEND:

——— = CONSTANT SPECIFIC-HUMIDITY LINES, INTERVAL 2 GRAMS PER KM (RELATIVE HUMIDITIES OMITTED FOR SAKE OF CLARITY)

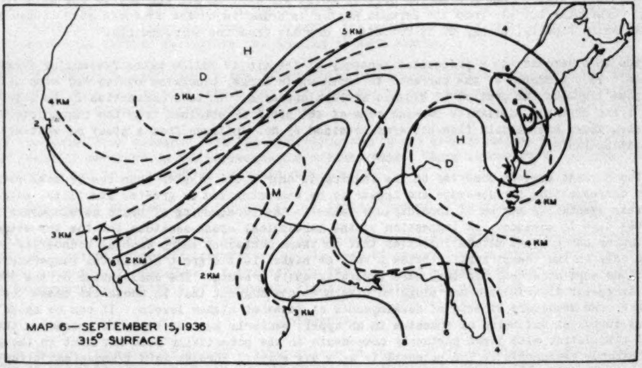
– – – = CONTOUR-LINES, INTERVAL 0.5 KM


4 KM
4 KM
4.5 KM
2
3.5 KM
3 KM
4
6
8
2 KM
10
2 KM
3 KM
10
D
2
6
8
ARROWS FLY WITH WIND

MAP 4—SEPTEMBER 14, 1936
315° SURFACE


4 KM
3 KM
2
2 KM
2 KM
3 KM
D
H
4
2
L
2
4 KM
1 KM
M
3 KM
1 KM
4
12
12
D
3 KM
2 KM
6
10
2 KM
8
10
2
ARROWS FLY WITH WIND

MAP 5—SEPTEMBER 14, 1936
310° SURFACE


2
3 KM
4
H
D
5 KM
4 KM
2
M
H
D
L
4 KM
4 KM
M
3 KM
4
6
2 KM
L
2 KM
3 KM
8
6
4

MAP 6—SEPTEMBER 15, 1936
315° SURFACE

GENERAL LEGEND:

H=HIGH L=LOW M=MOIST D=DRY

MAPS 1, 2, 3, 4, AND 6 SEPARATED BY 24-HOUR INTERVALS; MAP 5 IS FOR SAME DAY AS MAP 4 BUT FOR 310° SURFACE measurements too unreliable to be of any use for purposes of identification. For this reason isentropic surfaces with a mean elevation of two to three km were selected for study. Charts were prepared to illustrate the topography of, and the specific humidity-distribution in, these surfaces. Relative humidities were entered on the same charts to indicate the degree of saturation. Wind-directions and wind-velocities were obtained from the pilot-balloon records and entered in customary fashion. A separate set of charts was prepared to represent the weight (in millibars) of the layer between two specified isentropic surfaces above and below the surfaces of reference; these charts should give some information concerning convergence or divergence at intermediate levels in the troposphere.

In view of the smallness of the vertical velocity-components in the atmosphere one should expect the motion to be approximately parallel to the topographic lines, at least under steady or nearly steady conditions. A comparison with the observed winds proves this to be the case.

Up to the present, two synoptic situations have been investigated. Both are characterized by a slow advance northeastward of a moist and warm tongue, which makes its first appearance over Texas (El Paso). It is possible that the high moisture-content of this tongue may be caused by the intense vertical mixing attending the passage of air across the Mexican mountains. The steep lapse-rates observed at El Paso seem to support this hypothesis.

The northeastward movement of the moist air as measured by the displacement of the specific-humidity lines is generally slower than that indicated by the pilot-balloon data, showing a reduction in moisture-content of the advancing moist air through mixing with adjacent dryer air-masses. That this reduction does not result from vertical mixing, which apparently is quite insignificant whenever the lapse-rate has its normal stable value, is best seen from some vertical cross-sections for one of these periods which clearly show the remarkable persistence of even very thin layers of maximum or minimum moisture-content.

Explanation of Maps--Isentropic Maps 1 to 6 are part of a somewhat longer series analyzed by J. W. W. Osmun. Map 2 gives the location of all aerological stations used.

Lines of constant specific-humidity are drawn for intervals of two grams per kilogram (full lines). Contour-lines are drawn for intervals of one-half km (broken lines). The letters H, L, M, and D stand for high, low, moist, and dry. Relative humidities have been omitted for the sake of clarity in reproduction. The arrows on Maps 4 and 5 fly with the wind.

Maps 1, 2, 3, 4, and 6 refer to the 315° surface and are separated in time by 24-hour intervals. Map 5 refers to the same day as Map 4 but is drawn for the 310° surface. These two maps demonstrate the good agreement between the flow-pattern defined by the winds and the flow-pattern derived from the specific-humidity distribution.

On Map 1 a moist tongue from the southwest intersects a dry tongue from the northeast in such a fashion that on Map 2 a narrow belt of moist air extends all the way to the Atlantic Coast. Gradually dry air from the Bermuda Region is drawn in on the southern side of the moist tongue, which finally, on Map 6, is cut off by dry air from the surroundings.

The maps demonstrate a pronounced tendency of the air to follow paths resembling inertia-circles. This tendency of the currents to break up in large, clockwise eddies may eventually shed some light on the problem of dynamic anticyclogenesis. In this connection it is interesting to note the striking similarity between some of the patterns obtained from the isentropic charts described above and certain flow-patterns obtained by Mr. Spilhaus from a study of wake-streams, in rotating tanks.

The current-systems observed on the isentropic charts are simpler than the frontal patterns on the corresponding surface-maps and appear to be characterized by greater stability, suggesting that they eventually may be of considerable value in the forecasting of basic developments two or three days in advance. An inspection of the aerological cross-sections for the two situations analyzed by our present method indicates that on these occasions sharp frontal boundaries occurred only in the lowest strata (below 2 km); at higher levels great horizontal temperature-variations were observed, but they were generally quite gradual. The shallowness of the fronts, their irregular distribution and sluggish displacements suggest that in these two cases the fronts may have been secondary effects of developments at somewhat higher levels. It can be shown that lateral turbulent diffusion of momentum in an upper, westerly current tends to produce a transversal circulation with light northerly components in the potentially cold air next to the ground and southerly components in the potentially warm air above. Through this transversal circulation a steep horizontal gradient or front may be maintained next to the ground, in somewhat the same way as vertical mixing, according to Helmholtz [4], may lead to continuous frontogenesis near the ground.

Consideration of isentropic mixing may help to eliminate one difficulty frequently encountered in studies of American air-mass properties. A comparison of the average mixing ratios tabulated by Willett [5] for Ellendale, North Dakota, and for Broken Arrow, Nebraska, in winterly polar continental air-masses indicates that the moisture-content more than doubles along this fairly short trajectory. Similar increases have been noted by Namias [6] and most recently by Hewson [7]. In those cases where the evidence has not been rejected as resulting from unreliable observations of humidity, attempts have been made to explain the observed increases through turbulent transport from below, or through evaporation from precipitation falling through the air. The great stability of southward-moving, subsiding polar air-masses fairly definitely excludes the first explanation and the vertical distribution of the moisture-content excludes the second explanation, at least in the cases cited by Hewson. Dr. Willett informs me that he for some time has been of the opinion that lateral mixing alone can account for these marked changes in the moisture-content of advancing currents of polar continental air.

It can hardly be doubted that the isentropic charts represent the true motion of the air more faithfully by far than synoptic charts for any fixed level in the free atmosphere. At a fixed level in the middle of the troposphere entire air-masses may, as a result of slight vertical displacements, appear or disappear in the time-interval between two consecutive charts, making that entire method of representation futile. A comparison between the motion indicated by the constant specific-humidity lines in the isentropic charts and the motion indicated by the isobars for fixed levels, clearly establishes that the latter furnish extremely inadequate guidance for the determination of trajectories. This conclusion agrees well with the experience of marine biologists who in vain have attempted to explain the movements of various types of oceanic plankton with the aid of dynamic current-charts [8].

Convection and precipitation will often disturb the conservative nature of the isentropic weather-map. In the situations investigated by us, losses by precipitation were mostly eliminated through the selection of a sufficiently high surface of reference, but the addition of moisture through convection could not be avoided. A consideration of the vertical structure and the entry of relative humidities on the isentropic charts permit at least a qualitative estimate of the errors resulting from convection.

When the moisture-stratification is very pronounced it may happen that even relatively small errors in the potential-temperature determinations may result in a fictitious intersection between the reference-surface and the individual moist and dry strata. The resulting flow-patterns may then be highly misleading.

Conclusions

(1) The present-day aerological material from the United States is detailed enough to permit the construction of isentropic weather-charts; the substitution of radio soundings for airplane ascents will further facilitate the drawing of such charts.

(2) If caution is exercised in the selection of the proper isentropic surface, the air represented by such charts will remain the same from day to day; the charts will then be of great assistance in the study of current-trajectories.

(3) Flow-patterns obtained from the isentropic charts are simpler and more stable than the frontal patterns observed on the corresponding surface-maps. There is reason to believe that this stability may be of potential value in forecasting.

(4) The charts studied by us furnish strong indications of intense lateral mixing.

(5) Isentropic mixing must imply that true air-mass boundaries must be parallel to the surfaces of constant potential-temperature or, in case of saturation, to surfaces of constant equivalent potential-temperature. A preliminary inspection of a number of cross-sections analyzed at the Massachusetts Institute of Technology tends to confirm this deduction [see also 3, p. 305].

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THE USE OF 16-INCH BALLOONS FOR THE DETERMINATION OF UPPER-AIR WINDS

Loyd A. Stevens

Since January 1, 1921, the United States Weather Bureau has been using a standard-size pilot-balloon and a standard ascensional rate for the measurement of upper-air winds. The type of balloon adopted at that time was selected after more than two years of experimental ascensions had been made at several stations using different size balloons and different ascensional rates. These balloons are approximately six inches in diameter uninflated and weigh approximately 30 grams each. They are inflated with sufficient hydrogen gas to ascend at the rate of 180 meters per minute. For this particular type of balloon the ascensional rate of 180 meters per minute may be depended upon to be approximately uniform, except when convectional currents are encountered, up to a height of about 10 km, and then to increase slightly above that level up to at least 15 km. Above 15 km sufficient two-theodolite observations have not been made to indicate accurately the behavior of these balloons, as they are usually carried out of sight before such high altitudes are reached.

During recent years it has become increasingly obvious that larger balloons, capable of ascending at a more rapid rate and of reaching and being visible at higher altitudes, should be used for the determination of upper-air winds. For some time, for example, the advantages of flying at much higher altitudes than is now the practice along the present air-transport routes, has been a subject of investigation on the part of both the aeronautical engineers who must design suitable planes for such flights and the air-transport officials who will operate them. The results of these investigations indicate that regular flying at higher altitudes will be decidedly advantageous and will probably be an accomplished fact in the near future. To supply the necessary current wind-information for this high-altitude flying, larger balloons, of a type now under consideration, must be used as the smaller balloons, ascending at a slower rate, are too frequently carried out of sight before reaching the required altitudes. This is especially true when relatively high winds prevail in the lower levels. Under such conditions the horizontal motion of the balloon (caused by the wind) is so great as compared with the vertical motion (ascensional rate) that it is carried beyond the range of vision in a relatively short time and at a correspondingly low altitude. By using a larger balloon, on the other hand, the vertical motion can be appreciably increased and higher altitudes reached before the wind has carried it to such a distance that it is no longer visible. The use of the larger balloons will thus make it possible to add a considerable amount of much-needed information to our present meager knowledge regarding average winds at very high levels. Such information will be of great value both to meteorologists in their studies of the effect of conditions in the stratosphere on our surface-weather and to aeronautical engineers in their studies of the problem of high-altitude flying.

To meet the need for larger balloons, the United States Weather Bureau is now considering the use of balloons which are approximately 16 inches in diameter, uninflated, and which weigh approximately 100 grams. Preliminary two-theodolite observations made with these balloons at Omaha, Nebraska, November, 1936, revealed the fact that the ascensional-rate formula, developed from observational data based on the 6-inch balloons, does not hold for the larger balloons. Before the 16-inch balloons can be put into regular service for single-theodolite observations, therefore, it will be necessary to determine their ascensional rates as accurately as possible under different atmospheric conditions. A special series of two-theodolite observations has ac-

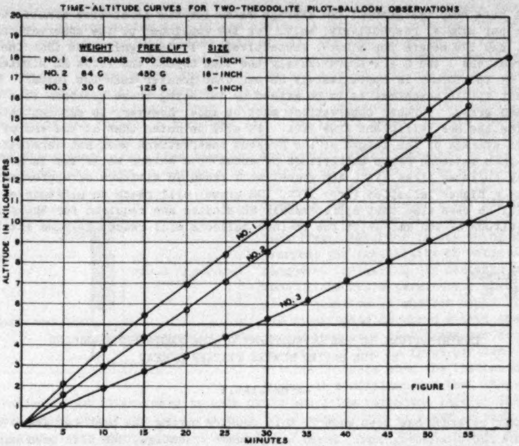
TIME-ALTITUDE CURVES FOR TWO-THEODOLITE PILOT-BALLOON OBSERVATIONS

FIGURE 1

cordingly been started in Washington, D. C., using the Weather Bureau observation-point at the Washington Airport as the location for one theodolite and a point near the Georgetown University Observatory for the other. The distance between these two points is approximately 3.1 miles. Communication between the two points is maintained by means of short-wave radio transceivers and the timing of the minute reading-intervals is regulated by an electric clock, located at the airport station, which operates a buzzer. The sound of the buzzer is picked up by an auxiliary microphone and transmitted to the other station by the transceiver so that the readings of both theodolites can be made simultaneously. Great care will be taken in measuring the amount of hydrogen gas used in the inflation of these balloons in order to determine their free-lifts as accurately as possible. To insure accurate angular readings, especially during long observations when the balloons are observed to great distances, it is planned to use special theodolites, equipped with magnified verniers which will give direct readings to 0°.01. A total of about 600 balloons will be released in all, over a period of several months and some of the more important facts which it is expected will be determined thereby are the following:

(1) The ascensional rates for different free-lifts and different-weight balloons.
(2) The diurnal and seasonal variation of convection (vertical currents) in the atmosphere under different sky-conditions.
(3) The variation of convection in different air-masses; this will be accomplished by correlating the results of these observations with those of daily airplane observations made by the Naval Air Station at Anacostia, D. C.
(4) The effects, on the ascensional rate, of attaching various weights and objects to the balloons, such as the small paper lanterns and electric lighting devices, which are now used in making upper-air wind observations at night.

When the series of observations has been completed, an ascensional-rate formula, applicable to this particular type of balloon, can be developed and a standard ascensional rate adopted for the regular single-theodolite observations.

From the observations made so far, it appears that the larger balloons will ascend at a rate of between 270 and 290 meters per minute when given a free lift of 450 grams. This is an increase of 50 to 60 per cent over the ascensional rate of the 6-inch balloons.

Figure 1--In Figure 1, time-altitude curves are shown for three representative two-theodolite observations. Curves 1 and 2 are based on observations made with 16-inch balloons at Omaha, Nebraska, during November 1936, and curve 3 is based on an observation made with a standard 6-inch balloon at Broken Arrow, Oklahoma, during July 1924. The circles indicate actual computed heights at the end of each five-minute interval. All three observations show the usual increase

in ascensional rate near the ground; the average rates for the first five minutes being 427, 316, and 212 meters per minute, respectively, while for the remainder of the observations the rates were 288, 278, and 178 meters per minute, respectively. It is significant that the ascensional rates of observations 1 and 2 are approximately the same beyond the first 20 minutes, although the free lift of the former is approximately 55 per cent greater than the latter. This appears to indicate that little advantage is to be gained by inflating these balloons to a free lift greater than 450 grams. Further observations must be made, however, to substantiate this fact and to determine the most efficient free lift. It will be noted that at the end of 20 minutes, which is a fair average of the length of the present observations when not terminated by low clouds, the 6-inch balloons reach an altitude of about 3600 meters while the larger balloons when moderately inflated (free lift, 450 grams) will reach an altitude of approximately 5700 meters and with a higher inflation (free lift, 700 grams) will reach an altitude of nearly 7000 meters. It will be seen also that approximately 55 minutes are required for the 6-inch balloons to reach an altitude of ten km, while the 16-inch balloons will reach the same altitude in 30 to 35 minutes.

U. S. Weather Bureau,
Washington, D. C.

CONTRIBUTIONS TO THE DEVELOPMENT OF THE RADIO-METEOROGRAPH BY THE UNITED STATES WEATHER BUREAU

D. M. Little

Considerable progress has been made in this country during the past two years in the development of the radio-meteorograph. Seven independent investigations have been carried on during this period with various models of instruments. The first successful model was developed by Dr. K. O. Lange of the Blue Hill Meteorological Observatory in cooperation with the Massachusetts Institute of Technology. The Olland system of telemetering was used in this instrument and the models were constructed by the Feiber Instrument Company. Other models of the Olland type were: One developed by Dr. L. F. Curtiss of the National Bureau of Standards in cooperation with the United States Weather Bureau and manufactured by the American Instrument Company; one developed by Captain O. C. Maier of the Army, and L. E. Wood of the Guggenheim Aeronautical Laboratory of the California Institute of Technology; one developed by Dr. J. Piccard and others of the University of Minnesota; one developed by Messrs. Mears, Little, and Moon of the United States Weather Bureau; and one now under development by the Julien P. Friez Instrument Company on a United States Weather Bureau contract.

An instrument, which does not use the Olland system of telemetering, has been designed by Messrs. Diamond, Hinman, and Dunmore of the National Bureau of Standards in cooperation with the Navy and models have been constructed by the Julien P. Friez Instrument Company. The instrument is designed to have the temperature- and humidity-elements control resistances in the circuit which modulate the continuous high-frequency transmission of a radio oscillator, and by having the pressure-element switch resistances in and out of the circuit in a definite order as the pressure changes during an ascent, a record is obtained at the receiving station of temperature, pressure, and humidity. This method eliminates the necessity of having a rotating mechanism in the instrument and overcomes the most serious limitation of the Olland type of instrument. With further development, the instrument has great possibilities.

By far the greatest amount of effort has been devoted by investigators in the field of radio-meteorology to the development of the Olland type of instrument. The United States Weather Bureau decided to concentrate its efforts on this type of instrument because of its relative simplicity. Consequently, a cooperative program was arranged more than a year ago with the National Bureau of Standards in which funds were supplied for the development of two designs, one by Doctors Curtiss and Astin and the other by the United States Weather Bureau. Clocks which were available at that time were very unsatisfactory and it was decided to experiment with other rotating devices. Messrs. Mears and Moon of the Instrument Division developed an air-rotor which was driven with dry air from a 6-inch pilot-balloon. Tests with this device indicated a rotor speed of approximately 5000 r.p.m. This was coupled to a gear-train taken from a watt-hour meter which had a gear-ratio of approximately 960 to 1. The assembly gave a rotating speed of about one revolution in 15 seconds for the contacting mechanism. Tests at room-temperature indicated that a 6-inch pilot-balloon, when initially inflated to a diameter of 26 inches, would drive the rotor for a period of 90 minutes with no appreciable change in speed from cycle to cycle. The overall change in speed between a balloon-diameter of 26 inches and 10 inches at room-temperature amounted to five per cent. A test-instrument was constructed to determine the action of the rotor under actual conditions of ascent. The contacting mechanism was designed for transmitting six equally-spaced impulses during each Olland cycle. A record was obtained for 68 minutes of a flight in which a red pilot-balloon filled with dry air was used to drive the rotor. The balloon and instrument were in the shade when the rotor was started and the contact-speed was one cycle in 14 seconds. Before releasing the instrument, it was carried into the Sun and the contact-speed decreased to one cycle in 21 seconds. The reduction in speed was probably due to a rise in temperature of the walls of the balloon. After it was released, the instrument-assembly was observed to oscillate and rotate in turbulent air. The record shows that the contact-speed was quite variable for the first 12 minutes of the flight when the instrument was in the region of turbulence near the ground. From that time on, the contact-speed increased as the walls of the balloon became colder and there is evidence to indicate that it was in the stratosphere during the last 19 minutes of the flight. The rotor-speed in the stratosphere was 240 per cent greater than it was near the surface of the Earth. A centrifugal governor is now being developed to overcome the variability of rotor-speed. The arrangement for having six contacts made during each Olland cycle permitted a study to be made of the question of whether rapid fluctuations of the rotor-speed occurred within the cycle. The record indicates that there was occasionally a variation of two to three per cent in rotor-speed within the cycle when the instrument was under turbulent conditions and that there was less than one per cent variation in rotor-speed in each cycle above the turbulent layer. The large fluctuation in speed under conditions of turbulence is presumably due at least in part to gyroscopic action of the rotor. The experiment indicates that similar tests should be made with all other rapidly rotating devices, such as the electric motor or very fast escapement-clock if used in a radio-meteorograph.

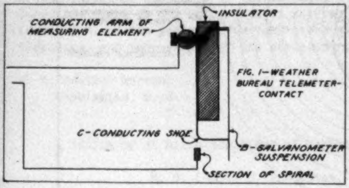
CONDUCTING ARM OF MEASURING ELEMENT
INSULATOR
C-CONDUCTING SHOE
D-GALVANOMETER SUSPENSION
SECTION OF SPIRAL

FIG. 1—WEATHER BUREAU TELEMETER-CONTACT

The problem of securing good electrical contacts and at the same time having a satisfactory system for enlarging the movements of the pressure-, temperature-, and humidity-elements, has been a perplexing one to most investigators. Dr. Lange solved the magnification-problem without the use of linkage- and lever-systems but the electrical contacts used in his instrument have not been entirely satisfactory. Mr. Mears of the Weather Bureau has developed a method, using a gold-plated cam shaped in the form of an Archimedes spiral, which is revolved once for each Olland cycle by the driving mechanism. The cam touches special contacting devices attached to the respective ends of the arms of each measuring element. The device consists of a fine gold spring mounted on an insulator and resting against a gold-plated shoe which is in contact with the arm. When the spiral touches the gold spring, the contact is made through the shoe, but, as

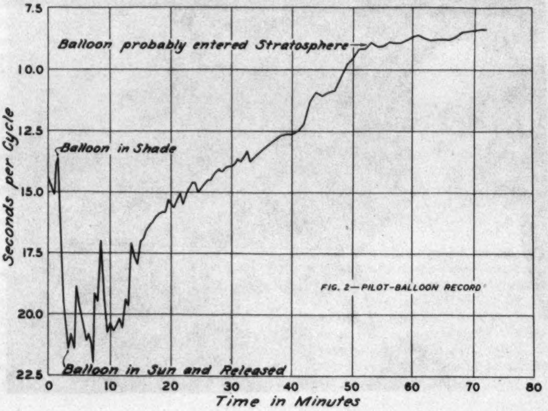

FIG. 2—PILOT-BALLOON RECORD

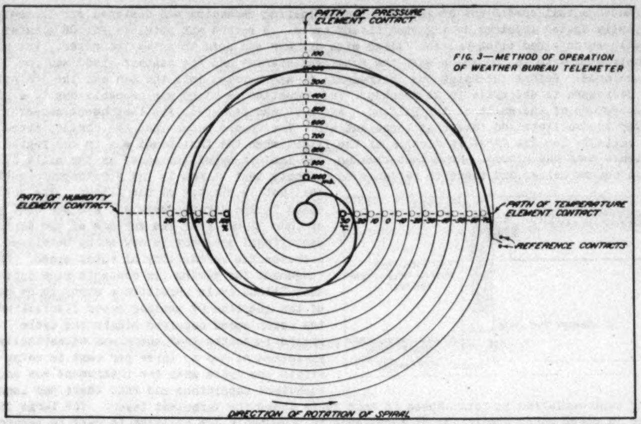

FIG. 3—METHOD OF OPERATION OF WEATHER BUREAU TELEMETER

PATH OF PRESSURE ELEMENT CONTACT
100
200
300
400
500
600
700
800
900
1000 mb.
PATH OF HUMIDITY ELEMENT CONTACT
20
40
60
80
100 %
30 °C
20
10
0
-10
-20
-30
-40
-50
-60
-70
PATH OF TEMPERATURE ELEMENT CONTACT
REFERENCE CONTACTS
DIRECTION OF ROTATION OF SPIRAL

the spiral rotates, the spring is pushed away from the shoe and the contact is broken. Finally, the spring slips off the spiral and again comes in contact with the shoe and is ready for the next contact with the spiral. The pressure-, temperature-, and humidity-elements are placed in such a position that at least one radius of the spiral is tangent to the arc traversed by the contacting device. With this arrangement, it is possible to use 100 per cent or more of the Olland cycle between maximum and minimum positions of the elements. It is understood that the Julien P. Friez Instrument Company is using this method on 20 instruments which are soon to be delivered to the United States Weather Bureau.

The problem of calibrating radio-meteorographs for daily flights is one which has not been solved to the satisfaction of the Bureau. In order to stimulate work on this problem and to further develop the radio-meteorograph, the Bureau has requested bids on the furnishing of 305

calibrated instruments at either Seattle, Burbank, Boston, or Washington, during September 1, 1937, to June 30, 1938.

To aid further in the development of a satisfactory radio-meteorograph for general use, as well as to secure necessary upper-air data in connection with investigation of cold waves in North America, by Wexler and others, it is planned to invite bids for 182 uncalibrated instruments for use at Fairbanks, Alaska, during September 15, 1937, to March 15, 1938.

Summing up, the United States Weather Bureau plans to have one and possibly two stations make daily radio-meteorograph flights, beginning September 1, 1937, with one station in Alaska equipped to make daily flights over a period of six months. Continued cooperation with the National Bureau of Standards is contemplated with direction-finding as one of the problems to be taken up. Work by the United States Weather Bureau in Washington will be concentrated on the improvement of the present motor and clock-work devices, the contact-system, the calibration-technique, and improvement of the strip-chart recorder to simplify the evaluation of records.

U. S. Weather Bureau,
Washington, D. C.

A SERIES OF 31 RADIO SOUNDINGS AT CAMBRIDGE, MASSACHUSETTS, IN FEBRUARY AND MARCH 1937

K. O. Lange, C. Harmantas, C. B. Pear, Jr., and D. P. Keily

On December 10, 1936, at 3:55 a.m., two small balloons, carrying a Harvard radio-meteorograph, were released from Blue Hill Meteorological Observatory, near Boston, Massachusetts. The radio-meteorograph measured the temperature, the humidity, and the pressure of the air at all heights up to 25,000 feet (8 km) and relayed this information back to the ground by a short-wave radio-transmitter contained in the instrument. The signals were received and recorded as a graph on the ground. The data obtained were immediately reduced and the weather-information relayed to the central office of the United States Weather Bureau at Washington, D. C. This radio sounding was the first successful radio sounding in America for the immediate benefit of the entire weather-service.

During December, 1936, six more ascensions were made, reaching as high as 70,000 feet (21 km). The data obtained by the radio-meteorograph were compared with the data simultaneously obtained by the Boston weather airplane up to 15,000 feet (4.5 km). They checked well save for the fact that all temperatures measured by the airplane were approximately 2° or 3° C higher than the ones measured by the radio-meteorograph. It was found necessary to conduct more ascensions in order to establish whether the radio-meteorograph or the meteorograph on the airplane was correct.

In connection with these seven ascensions a technique of operating the radio-meteorograph was developed which made it possible to dispose of the upper-air data faster than was possible with an airplane taking off at the same time that the balloon was launched. It was necessary to determine if this procedure could be used by others than the inventor of the radio-meteorograph.

In order to establish definitely that the Harvard radio-meteorograph was developed to such a state of perfection that it would yield better results than the airplane method, a series of 31 radio soundings was undertaken in February, March, and early April, 1937. The operation of the instrument was carried out by members of the meteorological staff of the Massachusetts Institute of Technology who had no previous experience with the instrument. The data obtained showed the same consistent deviation from the airplane data as did the December soundings, but in a paper given before the American Meteorological Society on April 28, 1937, by Karl O. Lange and Christos Harmantas it was established that the data of the radio-meteorograph were correct.

As a result of the experiences gained with the use of the radio-meteorograph to date, soundings can be made with much better regularity than those of an airplane, and in addition data can be made ready for transmission within a half hour after the end of the ascent. Although no attempt was made to maintain an exact schedule of releases during the 31 radio soundings, launchings were made about 5:40 a.m., and results were transmitted within two hours. If a routine schedule were now established, results can be on the wire in about one and one-half hours. Additional experimenting resulted in the change of battery-power in the radio-meteorograph. This more than doubled the average altitude. Due to this change, many radio-meteorographs reached heights of approximately 18 km, some instruments reaching 20 km.

Of the 31 instruments released, three records were lost, two being due to unsuccessful launching and the other having given a poor record. If releases had been made from a more favorable location, there would have been no losses at launching, and performance would have been still better. All of the instruments launched reached altitudes greater than those of the meteorograph on the airplane, and two-thirds of them entered the stratosphere.

Due to the fact that fair weather prevailed over long periods of time, the schedule of daily releases was broken in order to make as many tests as possible in bad weather. The last six instruments were released over a period of one month whenever very stormy weather occurred. Although this last group of instruments did not reach the average altitude, it is not necessarily a reflection on the performance of the instrument in bad weather because difficulties were experienced with this last group in their use in the laboratory. Quite possibly these last six instruments were not up to usual standard.

Although humidity-records did not show very good results, it is felt that this is entirely due to the rapid ascent of the balloon. Inasmuch as the thermal element of the radio-meteorograph is extremely sensitive, somewhat lower rates of ascent should be used in the future. This will give a better humidity record and a more detailed structure of the temperature-trace, making radio-meteorograph ascents more accurate, more convenient, yet still much faster, than soundings by airplane.

Blue Hill Meteorological Observatory,
Milton, Massachusetts

A FIVE-YEAR PROGRAM OF RESEARCH AND INSTRUCTION IN AEROLOGY AND AERONAUTICAL METEOROLOGY

Charles F. Brooks

The development of the radio-meteorograph now makes possible the investigation of aerological conditions in all kinds of weather and to great heights. There is reasonable prospect that a network of radio-meteorograph stations will be established throughout the United States within a very few years. It seems worth while, therefore, to outline briefly some of the main problems of aerology and aeronautical meteorology today toward the solution of which the radio-meteorograph will be very helpful. These are:

(1) Fog or low ceilings; heights and slopes of other cloud layers--vertical extent of fog or cloud, prospects of dissipation, relation to fronts and air-masses.
(2) Rough air--convectional, topographic, waves.
(3) Fronts and thunder-storms, lightning--especially ascending winds.
(4) Ice-formation--presence and height of icing conditions.
(5) Winds and weather at all heights, especially above 20,000 feet (not reached by regular weather airplanes)--current conditions and forecasts.
(6) Hurricanes and typhoons--winds and vertical motions, height.
(7) Variations in ultra-high-frequency radio transmission in relation to atmospheric stratification and fronts.

The Blue Hill Meteorological Observatory of Harvard University has outlined a program over the next five years involving a study of these problems in which it plans to cooperate with the Massachusetts Institute of Technology, the United States Weather Bureau, and the major airlines.

To realize the advantages to meteorology and aviation from bringing about a general adoption of the radio-meteorograph at an early date, continued use of the instrument in experimental ascents is essential. Thereby, the instruments, calibration-devices, technique of launching, receiver, recorder, and direction-finding equipment can be further improved and the use of radio-meteorographs made more effective, simpler, and less expensive. The upper-air data gathered will also be of value.

The United States Weather Bureau is taking a notable step in asking for bids on daily radio-meteorograph ascents at two stations beginning in September.

An essential phase of this research-project, if the knowledge gained is to be most effectively applied and more investigators trained and inspired, is the promotion of instruction of young college men, graduate students, and pilots in meteorology.

Blue Hill Meteorological Observatory,
Milton, Massachusetts

DETERMINATIONS OF SKY-BLUE

H. Landsberg and H. Jobbins

The determination of the color of the sky entered into modern meteorology with the introduction of the Blue-Scale by Linke and Ostwald [see 1 of references at end of paper], although de Saussure [2] had already made observations of that kind. The intimate relation between the blue color of the sky and the turbidity within the atmosphere, hence with such important elements as the intensity of radiation, the suspended impurities, and the visual range, made surveys of the sky-color desirable. The blue-scale, consisting of a set of cardboards with different shades of blue, is a very handy and cheap device, but its usefulness suffers from certain difficulties in operation. The matching of scale and sky-blue, in particular, often makes trouble, because of the discontinuities in the steps of the cardboard-scale. A simple instrument was therefore constructed, replacing the cardboard-scale by a glass-wedge. This wedge, made of the Signal Blue No. 556 of the Corning Glass Works, had its maximum transmission at about 425 millimicrons. It was movable by a sledge across an eyepiece, so that half of the field was open to the sky. The wedge was illuminated by a mirror, which reflected the sunlight. The thickness of the wedge varied from 0.025 to 0.584 cm on a length of 15.3 cm. In our observations a thickness of 0.23 cm was rarely exceeded to match the sky-blue. By mounting the instrument on a support with graduated circles the azimuth and altitude for each measurement could be determined.

On more than 100 occasions, observations were made at State College, Pennsylvania, to test the new device; a few results will be communicated here. In order to render the measurements comparable with blue-scale determinations in all instances, the sky-blue was also determined with a blue-scale of the second series, distributed by Linke (containing black). It was found that for the pale tints of blue an almost linear relation exists between wedge- and scale-determinations; for the higher blue-grades, however, the wedge-values increase less rapidly. The averages of the values found from 425 single measurements are given in Table 1.

Table 1--Comparison between blue-scale and blue-wedge

Scale blue number	3	4	5	6	7	8	9	10
Wedge-thickness in mm × 10^{-2}	13.5	40.7	67.0	106.8	136.2	148.5	152.9	175.1

Special attention was devoted to the relation between sky-blue and visual range, principally because it had been contended that sky-blue determinations might be used as indicators of the vertical visibility as it appears from an airplane. Hand [3] had found at Washington, D. C., that darker blue corresponded to better horizontal visibility. At State College, Pennsylvania, the blue was determined at an altitude of 5° above the horizon and 60° in azimuth 180° from the Sun. The values correlated to horizontal visual range are given in Table 2.

Table 2--Visual range and sky-blue in 5° and 60° above the horizon

Visual range, km	5-10	10-15	15-20	20-30	30
5°, wedge-thickness mm × 10^{-2}	13.5	17.3	25.4	20.8	20.8
60°, wedge-thickness mm × 10^{-2}	92.5	175.1	155.0	167.6	183.0

Table 2 indicates that very poor visibilities and pale sky are usually coincident. For the higher visibility comparatively little correspondence is observed with the exception that for excellent visibilities also a very dark blue is observed in 60° above the horizon. The irregular correlation is due to the position of the station in a mountainous region. There, after precipitation, a very dark-blue sky is often observed, while fog and haze still hang as an aftermath in the valley, impairing the horizontal visual range. A quite interesting relationship, however, was found between visual range and the variation of the sky-blue from the horizon to the zenith. In case of low visibilities, the rate of increase of the blue from the horizon upward was considerably less than in the case of high visibilities, as given in Table 3.

Table 3--Variation of sky-blue from the horizon to the zenith and visual range

Altitude above horizon	5°	15°	30°	45°	60°
Visual range, wedge-thickness mm × 10^{-2}					
Below 20 km	17.3	57.5	92.5	126.5	137.0
Above 20 km	25.4	67.1	111.9	139.7	167.6

On several occasions, measurements of the sky-blue were made in different azimuths and altitudes, covering one-half of the sky. In these determinations the advantages of the wedge over the scale became very obvious. The scale must always be fully illuminated by the Sun, and the observer is supposed to have his back to the Sun. With the scale, therefore, observations can be made only 180° from the Sun's azimuth. With the wedge there is no difficulty in making observations up to 90° in either direction from the Sun's azimuth because the mirror can always be turned to furnish proper illumination. As an example, the observation of blue-distribution over one-half of the sky on March 31, 1937, is given in Table 4.

Table 4--Blue-distribution over the sky

Azimuth from Sun		90°	110°	130°	150°	170°	190°	210°	230°	250°	270°
		Equivalent thickness of wedge in 10^{-2} mm									
Altitude	15°	134.9	134.9	294.1	518.0	558.0	355.9	332.5	294.1	172.5	172.5
above	30°	208.0	518.0	518.0	614.9	882.5	670.0	482.0	574.0	406.0	294.1
horizon	45°	354.9	451.5	670.0	558.0	735.0	735.0	735.0	735.0	406.0	483.0
	60°	134.9	332.5	483.0	574.0	574.0	558.0	517.5	208.0	254.0	102.8

The solar altitude during the determination was about 50°. This shows that the section 90° away from the Sun on the opposite side of the sky has actually the deepest blue. Similar results were obtained in several other cases on different days.

A more detailed study will be published elsewhere.

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THE AREAL FREQUENCY OF TORNADOES IN THE UNITED STATES BY COUNTIES, 1880-1931

Charles W. Brown and Wyndham O. J. Roberts

In this third paper of statistical studies of the distribution of tornadoes in our country in the recent half-century, the writers submit the county-distribution map with comments. It shows the results of the study of the distribution based upon smallest available unit.

Of course, it is understood that, under the inspiration of Colonel Finley's enthusiasm, the gathering of tornado-data was fairly comprehensive until the middle of the nineteenth century. A hiatus of a score of years then ensued in which tornado-facts were of rather fragmentary nature. But from 1916 on, some 5000 observers were cooperating in collecting fairly complete field-data. Of the 4000 tornadoes studied in this paper, about three-fifths occurred in this later period, and of the balance, the major portion occurred in the earlier period.

It is obvious that the more densely populated the region is, the more complete and accurate will be the returns of tornado-information, and that probably there is a more or less general relationship between the density of population and the reporting of tornadoes. The successive waves of settlement that progressed westward through the High Plains States in the last quarter of the nineteenth century undoubtedly increased the accuracy of the census of tornadoes--where any occurred. On the whole, a study of this phase of distribution shows the evidence first on one side and then on the other.

The different methods of graphical presentation may be seen in the dot map of tornado-occurrence by Finlay in 1887 [see 1 of references at end of paper]. Allan's map [2] of annual frequency published in 1930 shown by isotorns (if you will allow us to coin a handy term indicating lines enclosing irregular areas of equal tornado-frequency) to our track-map of the occurrence of tornadoes published in 1935 [3] and the detailed county frequency-map shown herewith (see Fig. 1). Dots may represent small circumscribed areas of occurrence and they in turn may be surrounded by successive lines denoting equal distribution-quantities. But it is difficult to find a correct method of illustrating the distribution of lines, such as tornado-tracks, which vary in length from a few miles to several hundred and are, withal, of relatively narrow paths. Hence, lines were broken down to square miles and rated then with the county-area in square miles. Upon considerable study of reports of tornado-tracks, it was thought that one-tenth of a mile or 176 yards would be a fair estimate of the average width of a tornado-track. Thus in the

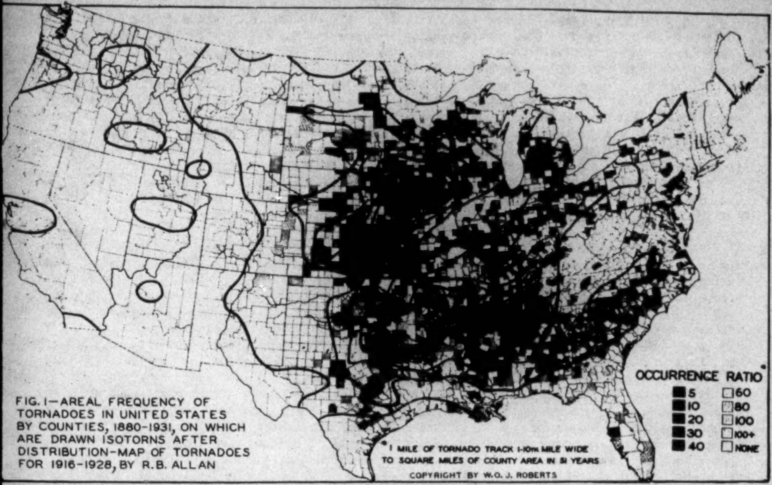

FIG. 1—AREAL FREQUENCY OF TORNADOES IN UNITED STATES BY COUNTIES, 1880-1931, ON WHICH ARE DRAWN ISOTORNS AFTER DISTRIBUTION-MAP OF TORNADOES FOR 1916-1928, BY R.B. ALLAN

*1 MILE OF TORNADO TRACK 1-10th MILE WIDE TO SQUARE MILES OF COUNTY AREA IN 51 YEARS

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51-year period studied (1880-1931) any county would be liable to so many miles of tornado-tracks one-tenth mile wide and not to so many tornadoes per county. For illustration, suppose a county with an area of 1000 square miles had in the half-century some 100 miles of tornado-damage of the one-tenth mile assumed width, blasted across its area, the liability ratio (10) of occurrence would be that any ten square miles (three miles square) might be subjected once to a one-mile-long tornado-track of devastation one-tenth mile wide. On the other hand, that 1000 square miles might have had, in the first assumption, 20 tornadoes with five-mile tracks or, secondly, three tornadoes with 33-mile courses. In the first of the above postulates, the rating by number alone would give it an abnormally high frequency-ratio (7) and the second a ratio much too low (1/7). But if the occurrence-ratio of the two were rated on an areal square-mile basis, the two cases would be equal. If a smaller practicable unit than the county could have been obtained, the conclusions would be even more accurate.

Another difficulty in using other types of graphical illustrations was found on the completion of the county-map. This hindrance was the existence of a large number (25) of "island" counties which have never experienced a tornado within their borders, yet are within and closely adjacent to areas of counties reporting tornadoes frequently.

One might think that the lack of tornado-paths in these particular counties might be due to a lower density of population and not to the absence of tornadoes. In Iowa, however, Delaware County, which has a high frequency of ten with a population decrease of 23 from 17,950 in 1880 to 1930, has on either side two counties, Buchanan (population in 1880, 18,546; 18231 in 1930) and Dubuque (population in 1880, 42,996; 57,000 in 1930), which never had a tornado in the half-century, in spite of a same or greater population.

In Michigan, Jackson County (population 72,539) is very low in frequency but is bordered to the north by Ingham County with a high frequency of ten (population 81,000) and Washtenaw, frequency 10 to 20 (population 49,527), to the east. Moreover, in Alabama and Mississippi and in Illinois, counties of low frequency, but with the same or greater population, are found bordered by counties with a very high frequency, of the same or even smaller population. So it would appear that tornadoes are no respecters of population and that they may or may not occur in counties of low or even of high density of population.

Furthermore, there were some 200 more counties not quite so close to the centers of high density but well within regions of considerable frequency that showed but from four to twelve miles of tornado-tracks in the 51 years. This "spottiness" prevents the drawing of contour-lines showing equal distribution without a too great sacrifice of accuracy.

The present map (Fig. 1) shows definitely that only towards the eastern margin of the rain-shadow of the Rockies does the tornado-density increase and that the western portions of the Plains States are relatively free from tornadoes. The 100° meridian of west longitude, the isohyet of 20", and the average relative-humidity line of 65 per cent all coincide to form the western limit of the distribution of tornadoes. The map also demonstrates clearly that the northern border of the central region is too cool or too far from cyclonic tracks to have tornadoes and that the seaward-margin of the coastal plain from Texas to New Jersey has but few tornadoes; that the Appalachians from hilly Georgia to New England do not breed these phenomena. The inner coastal plain and the Piedmont Region of the Southern States do, however, have a higher frequency. It will be noted further that, probably not due to the northeasterly trend of the Appalachian Mountains but to the characteristic northeasterly direction of both cyclonic and tornado-tracks, there is a decidedly northeasterly trend, not only to the areas of high, but of the regions of low frequency in the belt of the stormy westerlies.

The value of a county-map and its greater accuracy for scientific distributional purposes may be noted when there is superimposed upon it the last published map of annual tornado-frequency (Allan's, with 13 prolific years, 1916-28, using a unit of 100 miles square), as has been done in Figure 1. It is seen immediately that what might be considered density-centers by the isotorns have been shifted somewhat northerly from expectable high densities. But the inaccuracy of the Arkansas Center is indicated when we consider that the higher and inner isotorn of 3 to 3.5 tornadoes per year only varies in our occurrence-ratio by 0.35 square mile (14.00 versus 13.65) from the larger and lesser isotorn of 2.5 to 3. Included in this contour we find an "island" county with never a tornado in a period of nearly four times longer. A greater discrepancy occurs in the Oklahoma Center and a still larger one in the Kentucky-Tennessee Center where supposedly the denser frequency in the inner ring is exceeded by 50 per cent by the area outlined by the lesser-frequency isotorn. The occurrence of tornadoes in large areas west of the Rockies would seem difficult to explain on the basis of the 51-year occurrence of plotted tornadoes. It would seem to appear that the areas of high frequency would not be northeast Kansas but southeastern Kansas, north and east-central Mississippi, central Tennessee and Iowa, southern Michigan, with subsidiary highs in northeast Texas, southern Illinois, south-central Kansas, and central Arkansas. It might be said at this point that it is not the purpose of the paper to criticize other than constructively and to indicate a possible better method of handling difficult material or data.

These statistical studies are to be used as sign-posts indicating possible lines of research from which the origin and causal conditions of these phenomena may be derived.

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RESULTS OBTAINED FROM THE ANALYSIS OF NORTHERN-HEMISPHERE WEATHER MAPS FOR 1936-1937

Hurd C. Willett

Since October 1, 1936, the analysis of a continuous series of charts of the Northern Hemisphere, once daily, has been carried on without interruption at Massachusetts Institute of Technology. The reports used for each region are those coinciding most nearly in time with the 8 p.m. (eastern standard time) observations in the United States. Most of the necessary observations have been received directly by radio. However, the western Pacific and eastern Asiatic observations have up to the present been delayed two days beyond the others, for direct radio reception of these reports has been found difficult, so that it has been necessary to depend upon observations for this area mailed to us each day from the United States Weather Bureau in Washington. It is hoped that in the near future it will be possible to receive the broadcast of these data directly from Honolulu. Unfortunately one bad gap in the circumpolar distribution of observational data still remains--that of central Asia. However, it is usually possible, between the European Russian stations in the west and the eastern Asiatic observations, at least to get some idea of the larger features of the intervening pressure-distribution. Furthermore, it is hoped that in the near future it will be possible to receive directly the present broadcast from Moscow of central Asiatic reports.

The actual analysis has been carried out carefully. It requires close to three hours per map of the time of an experienced analyst. The general system of air-mass classification has been used rather than the local geographical system. The latter system applied to an entire hemisphere requires altogether too many different individual air-mass designations. In general, the analysis was not intended to give in minute detail the frontal structure of every disturbance--the scale of the map is too small, the station network scarcely dense enough, and the time-interval between maps (24 hours) is rather long to permit of this. But the effort has been made to locate carefully every important frontal zone, to locate, follow, and indicate the nature of every definite center of disturbance in each frontal zone, and to follow the principal air-mass movements and transformations. For the purpose for which this work was undertaken, the minor analytical details have little significance. It is rather the intensity and location of the principal centers of action of the general circulation, together with their effect on the position of the principal frontal zones and the major air-mass movements with which we are concerned.

There were really two immediate more or less definite general aims behind this daily analysis of Northern-Hemisphere weather-maps which was undertaken as one phase of a broad investigation of the whole problem of long-range weather-forecasting. These were (1) to acquire a practical acquaintance from day to day with the major features of the general circulation of the Northern Hemisphere and the broader interrelationships existing between the different branches of this circulation, and (2) to look for possible empirical clues as to the future state of the general circulation in its current state and present tendencies. Concerning the first of these points, it has been long realized by all practical weather-forecasters that there is a close correlation between the intensity and position of the principal centers of action and anomalies of the different meteorological elements over extended adjacent areas. The experience gained with the map of the Northern Hemisphere during the past winter, which was particularly rich in persistent anomalous conditions, completely verified this point of view. Fine illustrations were offered not only by the Bermuda High, but equally well by the other centers of action. The unusual development and westward extension of the Bermuda High was evidenced by the abnormal warmth in the eastern United States during the end of December and most of January, together with the extremely heavy rain along the frontal zone separating it from the cold continental anticyclone to the northwest. On the other hand, the complete disappearance of the Bermuda Center and its replacement by abnormally low pressure from the region of Bermuda northward, during the first week of February, brought the North Atlantic Coast the only week of subnormal temperature during the winter. Even more striking was the complete evacuation of the Aleutian Island Region of the North Pacific by the usual Aleutian Low, and its replacement by very persistent high pressure. This supplied the whole Pacific Coast with very abnormally cold Polar Pacific air-masses, and was responsible for the formation of the abnormally cold and persistent Polar Continental air-masses over the western half of the Continent. The usual mild maritime air of the North Pacific Area moved northward to Bering Sea and western Alaska. The frontal action on the Pacific Coast took place between the very cold continental air-masses and the cold Polar maritime masses. Consequently the precipitation was nearly all snow instead of rain, and each storm was followed by an outbreak of very cold Polar Continental air. Again, the Icelandic Low was as persistently present and overdeveloped as the Aleutian Low was absent. This was evidenced by an unusual persistence of severe storms over the North Atlantic and on the northwest coast of Europe.

Much more might be said about the complete dominance of the weather-conditions during the past winter over large areas by the vagaries of the individual centers of action and the frontal zones of interaction between these different branches of the general circulation. If this winter can be taken as typical, it would seem quite definitely that the establishment of the general circulation-pattern over the Northern Hemisphere is sufficient to determine the climatic characteristics of the corresponding period in most regions. But, of course, it is not at all justifiable to say that this constitutes an explanation of the prevailing conditions. It is no explanation whatsoever, but simply the manifestation in the general circulation of the existence of the conditions. To offer an explanation of the condition, it is necessary to find the underlying causes of the variations in the details of the pattern of the principal centers of action of the general circulation.

With regard to the second immediate aim of the present investigation, that of finding in the existing pattern of the general circulation over the Northern Hemisphere clues to coming changes or developments of importance in the circulation-system, very little success has been met with up to the present. In other words, there seems to be offered little hope of finding any empirical basis in such circumpolar charts for the preparation of general weather-forecasts one, two, or three weeks ahead, before the underlying physical causes of the anomalies in the general circulation are better understood. This result was, of course, anticipated, but it seemed desirable at least to make the effort. To aid in the search for such empirical indications, weekly mean-pressure maps for the Northern Hemisphere were prepared regularly, as well as isallobaric maps for the weekly pressure-changes. Such maps were found to be very helpful in bringing out the current trend, but the trends were found to be quite irregular as to their persistence, so that little evidence was to be found of imminent changes in the trend. However, it was found that the movement of the isallobaric highs and lows are much more significant than that of the isobaric highs and lows. Frequently the isallobaric systems move right through stationary isobaric systems, appearing as important changes in the intensity of the isobaric highs and lows, but without appreciable displacement of the isobaric centers. In general, it might be said that the movement of the isallobaric centers took place quite as often from east to west as from west to east, all centers around the hemisphere moving in the same direction at the same time. However, the same general direction of movement never persisted clearly for more than three weeks at a time. On several occasions there were conditions of stationary oscillation, in which every isallobaric center reversed its sign from one week to the next. The individual centers were too definitely identified by their shapes to permit of any possibility of confusion in identity. In connection with oscillations, it might be added that by and large, as nearly as could be estimated, the positive and negative isallobaric centers each week were approximately equal, that is, there is no indication of any appreciable general oscillation between the Northern and Southern hemispheres.

Although no progress has been made in the direction of finding any empirical basis of long-range weather-forecasting, the past winter's analysis of Northern-Hemisphere maps has been very stimulating to the writer by furnishing him with a rather definite picture of the general circulation-patterns of this Hemisphere which are associated with persistent anomalies of the meteorological elements over large areas, and by clarifying for him certain aspects of the problem of long-range weather-forecasting. Certain rather pronounced convictions in connection with this problem have been acquired, although they are not of the definite kind which can be rigidly proved, nor are they in considerable part original with the writer. They may be summed up about as follows:

(1) That there must be definite and persistent physical causes behind the more persistent anomalous circulation-patterns of the Northern Hemisphere. These patterns are far too irregular and persistent to be the result merely of the chance interplay of the elements of large-scale horizontal turbulence, or, in other words, of the migratory cyclones and anticyclones of northerly latitudes.

(2) That a real understanding of these underlying physical causes, and quantitative knowledge of the different factors involved, are going to be necessary for even an approximate solution of the forecast-problem. The complexity of conditions is such that empirical or statistical methods based on direct observation of only one or two elements are bound to lead to conflicting and inconclusive results. This will be true even if the elements considered are actually the controlling factors, unless it is understood just how they work. The preparation of the charts of the Northern Hemisphere will continue to be essential in the role of giving observational expression to the complex systems whose changes are to be forecast.

(3) That surface lag-tendencies, notably the effects of short-period glaciation or the irregular transport of ice and of cold-water or warm-water masses produced by temporary wind-systems, are of very secondary if not negligible importance in the control of the general circulation-pattern of the Northern Hemisphere, at least as far as the fluctuations from week to week are concerned. This is evidenced by the abrupt and complete reversal of the prevailing conditions which is frequently observed over large areas. Probably these surface lag-effects play somewhat more of a role at high than at low altitudes. It is possible, however, that these lag-effects may show in longer period anomalies of small amplitude.

(4) That it seems to be the vast subtropical anticyclonic units in the general circulation which are the prime movers in all important and persistent changes. The cyclonic units at high latitudes, although completely dominating local conditions, appear to depend in both their location and development on the behavior of the great primary subtropical units. Since surface-conditions in the subtropics change comparatively little, this would seem to suggest that the essential factors of control are operative directly at upper levels in the atmosphere, whence the effects are recorded indirectly at the Earth's surface in the general circulation-pattern with its attendant anomalous distribution of the meteorological elements.

The author wishes to acknowledge the cooperation of Messrs. J. Holmboe and J. Namias in the daily work of analyzing the Northern-Hemisphere maps.

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AMERICAN GEOPHYSICAL UNION

Eighteenth Annual Meeting

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

Washington, D. C.
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PAPERS.

THE 23-, 46-, AND 92-YEAR CYCLES IN SOLAR AND TERRESTRIAL PHENOMENA

C. G. Abbot

(Abstract)

The variation of the solar constant of radiation discloses at least 12 periodicities which are approximately aliquot parts of 23 years. There is also the 23-year cycle in sunspot-numbers and in solar magnetic conditions. The cycle of 23 years was also noted by Wild in his discussion of the temperature-departures of St. Petersburg, and both 23- and 46-year cycles therein were illustrated. Whipple has referred to the 23-year cycle in the temperature-departures of Adelaide. The author finds not only this cycle but the subordinate solar cycles in both temperature and precipitation in Helsingfors, Berlin, Copenhagen, Greenwich, Capetown, and Adelaide.

Douglass finds the 23-year cycle in many seriesof tree-ring measurements. The author showed slides displaying cycles of 23, 46, and 92 years in the widths of tree-rings at Fairlee, Vermont. The 46-year cycle appears to be particularly important in precipitation. It seems to have recurred regularly, affecting tree-ring widths at Fairlee, for four centuries. Its recurrence there is nearly in the same phase as the variations of level of the Great Lakes for the past century. We seem justified in expecting a recovery from drought-conditions in the Northwest within a year or two, but a severe recurrence of them following the year 1975.

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RADIO BALLOON-MEASUREMENTS OF THE COSMIC RADIATION

Thomas H. Johnson

Cosmic-ray data from the stratosphere can be obtained on free, unmanned balloon-flights either by recording directly in the gondola of the balloon and finding the apparatus afterwards or signals may be transmitted by radio from the balloon to a recording station on the ground. The former method is limited to civilized areas so that studies covering a wide range of latitudes demand the use of the radio transmitter. The measurements may be carried out with either ionization-chamber or Geiger-Mueller counter technique. The latter, when used in coincidence, has the advantage of being able to select rays from a particular direction or to select cosmic-ray events of a particular type, such as showers, the passage of heavily ionizing rays, etc. For studies of the geomagnetic asymmetry the directional selectivity is required. Also in the case of measuring intensities as a function of elevation or of latitude, there is a considerable advantage in limiting the measurements to a single direction.

The technical problem has three essential requirements: The apparatus must be light in weight, low in cost, and it must be reliable in operation. Large numbers of flights will be required in getting the data needed since there is a large number of problems for which the method is applicable.

The apparatus now in use weighs eight pounds and costs less than $20. The cost of balloons and hydrogen increase the expense of each flight to about $35, exclusive of time of the investigator and helpers in the shop.

The conventional type of circuit with some modifications is used for selecting the coincidence-discharges of the counters. When such a coincidence occurs, a keying relay is closed for a protracted time of the order of 1/50 second and voltage is applied to the plate-circuit of a 41 megacycle, self-excited, push-pull oscillator, which sends out a "dot"-pulse of radio energy. At intervals of about one minute, a short time--of the order of ten seconds--is devoted to the transmission of signals indicating the barometric pressure and the temperature. The former are of the nature of a sequence of dashes easily distinguishable from the cosmic-ray dots and the total number of such dashes indicate the number of contacts sealed into the tube of a mercurial barometer which, at the time, are flooded with mercury. About 25 such contacts are usually provided, and a previous calibration determines their significance. Since neither the barometer nor other parts of the apparatus are sensitive to temperature, only three temperature-signals are used to indicate temperatures below 0° C, above 40° C, or in the interval between. These signals consist of a rapid periodic sequence of dots determined by the resistance and capacity in a neon-tube flicker-circuit, the constants of which are varied between three values by a bimetallic contact-bar.

Voltage for the cosmic-ray circuit and for the radio transmitter is supplied by a 180-volt battery weighing 1.6 kg. The continuous drain is 1.6 ma, but at the time of a signal the transmitter-current is about 50 ma. Although it would be possible to use a considerably lighter battery than the one adopted, the increased cost of lighter batteries more than offsets the saving in hydrogen for lifting the heavier ones. The counters are sensitized with 1280 volts obtained from the B-battery by a condenser multiplying device. This consists of a rotating contactor which makes a momentary connection at each revolution between the battery and pairs of taps from each of a bank of six 2-microfarad condensers. These are connected permanently in series through one-megohm resistors but they are thus charged in parallel. The time between chargings is adjusted to restrict the variation of potential to a tolerable limit of a few volts so that counter-sensitivities remain constant. The device has advantages over a high-voltage battery in regard to reliability, weight, cost, and durability. The power for driving the contacts is obtained from a gravity-motor constructed of alarm-clock parts and a spool of cord by which the apparatus is suspended from the balloon. With a rate of fall of two meters per hour, the power is ample for the requirements.

Balloons made by the Dewey and Almy Chemical Company have been used. Four 350-gram balloons tied in two pairs, the upper ones on 30-foot cords and the lower ones on 20-foot cords, have behaved satisfactorily in flight and have seemed to show less of a tendency to swing and bump when suspended in this way. These are usually inflated for a rate of rise of 6.5 miles per hour, with a residual rise of 3.5 miles per hour if one balloon bursts. The bursting of two balloons allows the apparatus to fall slowly to Earth.

In order to avoid interference with the radio signals produced by local man-made disturbances, the receiver has been located on the observation-platform of the Hopewell Fire-Lookout Tower of the Pennsylvania Department of Forests and Waters. This is remotely located with respect to automobile roads and electrically operated machinery. The receiver is of the super-regenerative type and its sensitivity is such that the reception from the transmitter is entirely limited by the level of noise from remaining disturbances. Since most of this disturbance is man-made, a considerable advantage will be realized in removing the receiving point still further from civilized areas. On a flight made from the summit of Mt. Washington, New Hampshire, no appreciable diminution of signal-intensity was observed until after about two hours, when the signals suddenly ceased, presumably from the falling of the balloon. The results obtained on the above flight were in approximate accord with those obtained by other observers in the same latitude, but, because of an uncertainty in the pressure, no reliance can be placed in them.

This work is being carried out under grants from the Carnegie Institution of Washington, to whom acknowledgment is made. A more complete account of the developments at a slightly earlier stage of the work is included in an article in the Journal of the Franklin Institute (v. 223, p. 339, 1937).

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GEOGRAPHIC ASYMMETRIES OF COSMIC RAYS AS RELATED TO THE EARTH'S MAGNETIZATION

M. S. Vallarta and William P. Jesse

It has been shown [see 1 of references at end of paper] that the known magnetic field of the Earth may be closely approximated by that of a magnetic dipole of strength 8.1×10^{25} Gauss-cm at the magnetic center of the Earth. This center is situated at a point 340 km from the geographical center. Its latitude is 6°5 north and longitude 161°5 east. The extension of the axis of the eccentric dipole pierces the Earth's surface in two points, one at latitude 80° north in longitude 83° west and the other at latitude 76° south in longitude 121° east. These points are labeled NPED and SPED, respectively, in Figure 1.

According to the theory of Lemaitre and Vallarta [2, 3, 4], cosmic rays, as electrical particles distributed isotropically in space, are bent by the Earth's magnetic field and some of these are shot back to infinity while others are allowed to reach the Earth's surface. At any

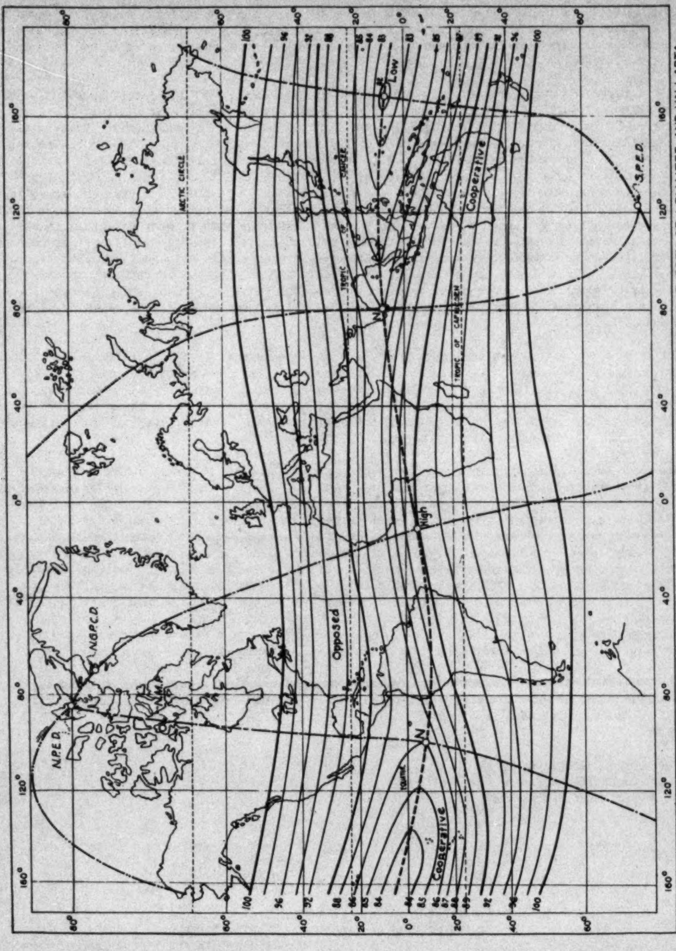
Low
High
Cooperative
Opposed
S.P.E.D.
N.G.P.C.D.
N.P.E.D.
N.M.P.
ARCTIC CIRCLE
TROPIC OF CANCER
TROPIC OF CAPRICORN
100
96
92
88
86
85
84
83
0°
20°
40°
60°
80°
120°
160°

FIG. 1—MAP SHOWING LINES OF EQUAL COSMIC-RAY INTENSITY AS CALCULATED FROM THEORY OF LEMAITRE AND VALLARTA

point a given distance from the Earth's magnetic center, all particles of a given energy reaching that point are included within a cone of very complicated shape which forms a boundary for the region where all directions are allowed and separates this region from other regions where only some or no directions are allowed. In any allowed direction, moreover, the intensity is just the same as would exist in the absence of the magnetic field and hence the same as it is at infinity. Since the boundaries of these cones may be determined from the theory, the intensity of the cosmic rays of a given energy may be calculated for the point in question, situated at a given distance from the magnetic center of the Earth.

If one considers the magnetic field of the Earth to be represented by that of the eccentric dipole mentioned above, then the magnetic center of the Earth does not coincide with the geographic center. Therefore, the distance from the magnetic center of the Earth to any given point on the Earth's surface becomes a periodic function of the longitude, being sometimes greater than the standard radius of the Earth and sometimes less. The aperture of the allowed cone for cosmic rays at any given point is a function of the distance of that point to the magnetic center. Two points of the same geomagnetic latitude on the Earth's surface may have, in general, different distances from the magnetic center. Hence, because different angular apertures of the cones result, the intensity of cosmic rays reaching the two points will be different. The eccentric dipole, therefore, introduces a longitude-effect [3] into the theory of cosmic-ray intensity distribution.

To compute the cosmic-ray intensity at any point on the Earth's surface, the calculations may be briefly outlined in the following steps. For a given point of geographic coordinates (α, β) one can easily compute the geomagnetic latitude λ [5] and the distance ρ from the point in question to the Earth's magnetic center as chosen above. From the theory of the allowed cone [2] of cosmic radiation there may be found the least energy a particle must have to arrive at that point through the Earth's magnetic field. This limiting energy is calculated in two steps: First is found the limiting energy for the corresponding geomagnetic latitude λ; second, this value is then multiplied by the ratio (ρ/R), R being the Earth's radius. Let $r_{\lambda\mu}$ be the limiting energy at that point. By Liouville's theorem the cosmic-ray intensity at that point is

$$I_{\lambda\mu} = \int_{r_{\lambda\mu}}^{\infty} f(r)\,\omega_{\lambda\mu}(r)\,dr$$

In this expression f(r) is the energy-distribution function of primary rays, which is as yet unknown. As a working hypothesis it is assumed to be an exponentially decreasing function of energy extending from 300 millistörmers (ms) to infinity. The threshold at 300 ms is obtained from the fact that certainly the intensity remains practically constant at sea-level beyond geomagnetic latitude 50° and possibly this remains true even at the highest altitude yet reached. $\omega_{\lambda\mu}(r)$ is the solid angle of the main cone as a function of energy at the given point, which is obtained from theory [3]. The variable r is a pure number measuring the energy of the particle in störmers [4]. The indicated integration may be carried out graphically or mechanically.

The above calculation has been made by one of us for a sufficient number of points outside the geomagnetic equator to determine without ambiguity a few of the curves of constant intensity on the Earth. At the geomagnetic equator such calculations have already been made in the computation of the longitude-effect [3]. The remaining curves in Figure 1 were determined by interpolation. No attempt at high precision has been made. It should be borne in mind that the theory, since it does not take atmospheric absorption into account, can give only for each one of these curves the relative intensity outside the atmosphere. Since a curve of constant intensity outside the atmosphere should correspond to a similarly located curve on the Earth's surface, the lines on the map have been labeled so as to give roughly the known latitude-effect at sea-level. This labeling is, therefore, wholly arbitrary. The test of the theory as well as of the initial assumptions as to the position of the magnetic center of the Earth consists, therefore, in verifying whether the position of the observed lines from actual cosmic-ray surveys agrees with the position of the calculated ones. The theoretical results presented here are subject to possible revision pending a final analysis of the effect of the Earth's "shadow." It need hardly be emphasized also that the assumed distribution-function is wholly arbitrary; if the actual spectrum differs considerably from an exponentially decreasing function of energy, additional modifications will be introduced.

As to the details of Figure 1, it may be noted that the double-dot-dash lines passing almost vertically through the points marked "High" and "Low" on the map are the lines along which the distance from points on the Earth to the magnetic center are greatest and least, respectively, for the same geomagnetic latitude. Thus, of all points along the geomagnetic equator, the maximum intensity is found off the west coast of Africa at the point marked "High" at longitude 12° west, while the minimum is at the point marked "Low" in the Pacific Ocean at longitude 168° east. The dot-dash lines through the points marked N on the map are (very nearly) lines along which the distance from points on the Earth's surface to its magnetic center is equal to the Earth's radius. Along such lines one gets the "normal" latitude-effect, that is, the latitude-effect uninfluenced by the longitude-effect. The intersection of such lines with any geomagnetic parallel must give points of equal cosmic-ray intensity. Thus on the map, the two points N, which represent the intersections with the geomagnetic equator, have the same value for cosmic-ray intensity.

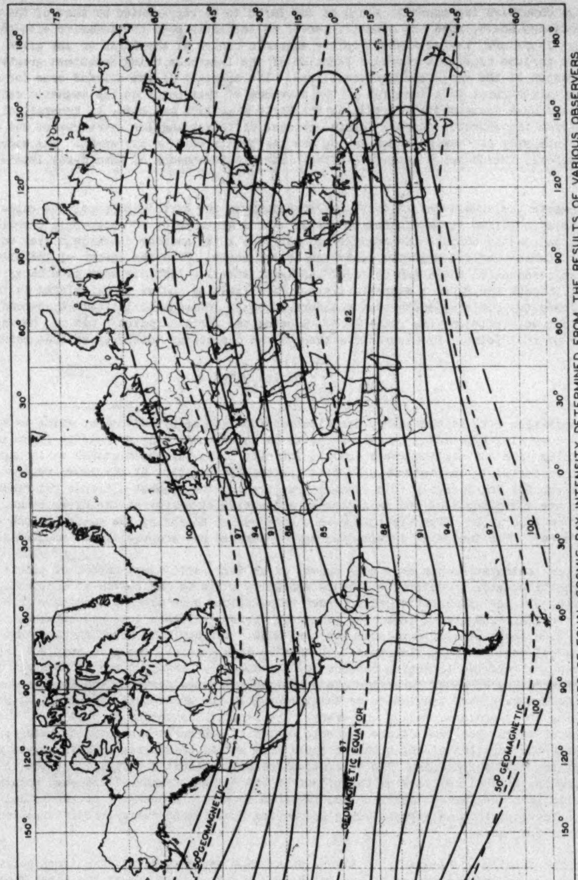

FIG. 2—MAP SHOWING LINES OF EQUAL COSMIC-RAY INTENSITY DETERMINED FROM THE RESULTS OF VARIOUS OBSERVERS (BASED ON MAP OF 1936 BY A. H. COMPTON)

When we come to compare the theoretical predictions with the results of experiment, we see certain apparent discrepancies. In Figure 2 is shown a map derived from the cosmic-ray surveys of various investigators including Compton, Clay, Hoerlin, Millikan and Neher, and Prins. This is essentially the same map already published by Compton [6] except that the lines of constant cosmic-ray intensity are now labeled in per cent of the maximum intensity, and minor changes have been made in the shape of the lines of the Pacific Ocean in the light of more recent data. This map shows in the vicinity of the geomagnetic equator a minimum near Sumatra at not more than 100° east longitude and a maximum off the west coast of South America at very approximately 100° west longitude, while the theoretical map of Figure 1 shows minimum and maximum at longitudes

168° east and 12° west, respectively. If then the theory is assumed to be correct, there seems to be a serious discrepancy in the position of the magnetic center of the Earth between the results from magnetic data and those from cosmic-ray data, since the longitudes of the positions of the maximum and minimum intensity depend only on the coordinates of the Earth's magnetic center, particularly its longitude. The cosmic-ray data would indicate a position of the magnetic center at longitude not more than 100° east instead of 160° east. Such an apparent discrepancy has already been pointed out by Hoerlin [7] from consideration of both his own data and those of Compton as compared with theoretical predictions. The chart of Millikan and Neher [8] for their recent sea-level survey, though not in good agreement with those shown in Figure 1 especially at the higher latitudes, shows practically the same position for the minimum at about longitude 100° east.

On the other hand, some cosmic-ray results have been reported which are definitely not in agreement with the results shown above in Figure 2. Bowen, Millikan, Korff, and Neher [9] report from airplane observations up to 26,000 feet in Peru and the Philippines (both practically on the geomagnetic equator) that a difference of cosmic-ray intensity of no more than four per cent exists between those two places even up to the highest altitudes reached. In addition to this, a minimum of intensity has been reported by Clay, Bruins, and Wiersma [10] off the western coast of South America. Both of these results would indicate an actual distribution of intensity more closely resembling the theoretical predictions and would, therefore, argue for the correctness of the initial assumptions as to the position of the Earth's magnetic center. It would seem, therefore, extremely rash to assume that the discrepancy between the results of magnetic measurements and cosmic-ray measurements is necessarily a real one. While the preponderance of available cosmic-ray data would indicate a position for the magnetic center of the Earth somewhat different from that given by magnetic data, it is doubtful whether the phase of the longitude-effect has been experimentally determined accurately enough at present to justify such a conclusion. More extended and more accurate data are definitely needed to settle the question.

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REPORT OF COMMITTEE ON DISSEMINATION OF MAGNETIC DATA OF AMERICAN-OPERATED MAGNETIC OBSERVATORIES

E. O. Hulburt, S. S. Kirby, A. K. Ludy, and A. G. McNish

Terrestrial-magnetic information included in the cosmic-data announcements disseminated through Science Service is provided by the daily character-figures from the Cheltenham Magnetic Observatory of the United States Coast and Geodetic Survey. It is well known that the Cheltenham figures are excellent indicators of world-wide magnetic activity. However, the figure from Cheltenham, or any other single station, does not, and inherently can not, give an exact quantitative measure of world-wide activity. This is due partly to the fact that magnetic activity is not always uniformly distributed over the Earth, and partly to the circumstance that each station is constrained to record its figure on the international scale of three steps, namely, 0, 1, and 2. For example, during a day of moderate magnetic disturbance a station may report 0, whereas the international figure, being an average of about 40 stations, some of which may record 1, may be 0.4.

It seemed desirable to modify, or supplement, the magnetic information by providing instead of, or in addition to, the Cheltenham figure a number which would approximate more closely to the world-wide character-number. There are seven magnetic observatories under American control, namely, Sitka (Alaska), Cheltenham (Maryland), Tucson (Arizona), Honolulu (Hawaii), San Juan (Puerto Rico), of the United States Coast and Geodetic Survey, and Huancayo (Peru) and Watheroo (Western Australia) of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. These could report magnetic conditions with the promptness necessary for the cosmic-data announcements of Science Service. Although few in number, the observatories are widely distributed extending from 57° north to 30° south in latitude and from 116° east to 285° east in longitude, and thus are fairly representative of world-wide conditions.

In Figure 1 is illustrated the comparison between the average magnetic character-figure of the seven American observatories and the world-wide figure for the first half of 1929. The daily character-numbers of each of the seven stations were added and the result divided by seven, the values being plotted in the heavy line of Figure 1. The world-wide values from "Caractere magnétique," published at De Bilt, are given in the shaded areas of Figure 1. The heavy line is in fair agreement with the shaded areas except that on the whole it lies below the summits of the shaded areas. Similar curves for other years, including sunspot minima and maxima, led to the same conclusions.

The reason that the American average was usually less than the international average becomes apparent when the records of individual stations are examined. The character-numbers of the 42 stations of the international list for each day of the year 1930 were added and are plotted as abscissas in Figure 2; the ordinates are the latitudes of the station; the American stations are shown by crosses and the other stations by dots in Figure 2. The character-numbers of the dots are considerably greater than of the crosses, particularly for the group of dots around latitude 50° north which refer mostly to European observatories. Therefore, the international world-wide figure, which is derived from all the points of Figure 2, is of course greater than the American figure which is derived from the crosses. Plots similar to Figure 2 for other years led to the same conclusions. The reason that the character-figures of European stations are greater than those of American stations is probably not due to greater magnetic activity in Europe than elsewhere but is rather to be attributed to differing criteria of magnetic characterization among the various groups of stations. At present there is no clear reason for saying that one criterion is more correct than, or preferable to, another.

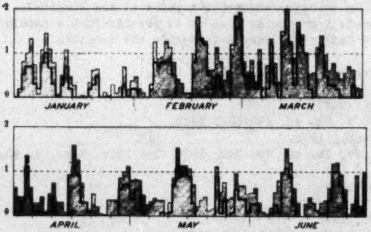

FIG. 1—MAGNETIC CHARACTER-NUMBERS FOR THE YEAR 1929

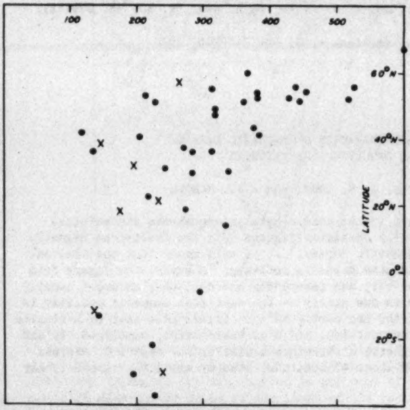

FIG. 2—SUMMATION OF DAILY INTERNATIONAL MAGNETIC CHARACTER-NUMBERS FOR YEAR 1930 AT 42 OBSERVATORIES, PLOTTED AGAINST LATITUDE—CROSSES INDICATE THE SEVEN AMERICAN-OPERATED OBSERVATORIES

Analysis of the records of the seven American stations indicated that each station was of equal importance in its contribution to the average character of the day.

It appeared advantageous to modify the international character-scale by inserting two more steps, 0.5 and 1.5, yielding a scale of five character-numbers, namely, 0, 0.5, 1, 1.5, and 2. Thus, in case the magnetic observer were undecided whether to report 0 or 1, as often occurs, he could express his indecision by reporting 0.5. Since the magnetic character-figure is often used in connection with world-wide phenomena, such as radio communication, which are concerned with intervals of less than a day, it seemed desirable to provide a magnetic character-figure for each half of the Greenwich day.

As a result of the foregoing considerations the following plan was put into effect during March, 1937:

(a) The seven magnetic observatories Sitka, Cheltenham, Tucson, Honolulu, San Juan, Huancayo, and Watheroo, assign character-numbers, on a scale of 0, 0.5, 1, 1.5, and 2, to each half of the Greenwich day.
(b) The 14 character-numbers of each observatory for the week ending midnight, GMT, Friday, are received on the following Monday or Tuesday by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.
(c) The respective character-numbers from the seven stations for each half-day are averaged by the Department of Terrestrial Magnetism and the 14 numbers for the week are transmitted to Science Service on Tuesday.
(d) Science Service includes the 14 average character-numbers in its weekly "Cosmic-Data Bulletin" mailed each Wednesday.

In announcing this new index of magnetic activity, attention should be called to the vital part played by the observers at the seven magnetic observatories, the communication-service of the United States Army and the United States Navy, and several radio amateurs upon the faithful prosecution of whose services the success of the undertaking depends. Persons employing the new character-figure in radio and magnetic investigations are greatly indebted to them.

Naval Research Laboratory (EOH),
U. S. Coast and Geodetic Survey (AKL),
Carnegie Institution of Washington (AGM),
National Bureau of Standards (SSK),
Washington, D. C.

EARTH-CURRENT VARIATIONS WITH PERIODS LONGER THAN ONE DAY

W. J. Rooney

(Abstract)

Examination of the earth-current records from Tucson and Huancayo shows that the daily mean values recorded on characteristically disturbed and calm days differ consistently by a small amount. This suggests that a part of the current flowing during disturbances or magnetic storms is unidirectional for the day or longer and is the first definite indication of a component in earth-currents with period greater than one day. The magnitude of the effect is small, not more than a few per cent of the range of diurnal variation at a given station. The direction of flow indicated is to the north and east at Tucson and to the south and east at Huancayo. These directions are consistent with those noted in the diurnal variations but they may be modified by local geological features. The reversal of direction of the northward component is also a feature of the diurnal variations when the stations considered are on opposite sides of the equator. The potential gradient due to earth-current flow is so small at Watheroo, in proportion to the large and irregular contact-potentials occurring there, that the Watheroo records are not conclusive on this point. In so far as they have any significance, the results are in agreement with those at Huancayo and consistent with the preferred direction of current-flow found in the diurnal-variation records. A wider distribution of stations and a more accurate quantitative measure of the effect is necessary before attempting to suggest a system of current-circulation consistent with these results.

[The complete paper is published in the Journal of Terrestrial Magnetism and Atmospheric Electricity (v. 42, pp. 167-174, 1937).]

Department of Terrestrial Magnetism,
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Washington, D. C.

AN ASTATIC MAGNETOMETER FOR MEASURING THE SUSCEPTIBILITY OF MATERIALS FOR MAGNETIC INSTRUMENTS

E. A. Johnson and W. F. Steiner

(Abstract)

It is well recognized that one serious source of error in the absolute measurement of the Earth's magnetic field lies in the use of materials of high magnetic susceptibility in the construction of magnetometers and other magnetic instruments. A rugged instrument has been developed which allows a rapid and accurate measurement of the absolute susceptibility of any material having a susceptibility of 1×10^{-8} electromagnetic cgs unit or greater for a wide range of geometrical shapes.

The instrument consists of an astatic magnetometer in which the magnets are accurately balanced against each other; the magnets are suspended by a 7-micron diameter fiber of quartz. The material under test is brought close to one end of the magnet-system and the deflection noted. The magnetometer is then calibrated by bringing a hollow full-scale model of the specimen--the model being filled with a chemical of known susceptibility--to the same position with respect to the magnet-system. Since it has been determined that the deflection of the magnetometer is proportional to susceptibility of the specimen, the two deflections depend only on the respective susceptibilities. A small Helmholtz coil is provided around one magnet in order that a null-method may be used if the susceptibility is high enough to cause greater than full-scale deflection. For small cylindrical specimens the sensitivity is as high as 1×10^{-9} electromagnetic cgs unit, while for other shapes it is 1×10^{-8} electromagnetic cgs unit, and can be made as insensitive as may be desired. A single measurement requires only a few seconds, apart from the time required to prepare the model used in calibration.

[The complete paper is published in the Review of Scientific Instruments (v. 8, pp. 236-238, 1937).]

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

A ZERO DISTRIBUTION-COEFFICIENT FOR HORIZONTAL-INTENSITY MAGNETOMETERS

Geo. Hartnell

To obtain the correct absolute value of H, the horizontal intensity, at different deflection-distances by means of a magnetometer, it is necessary to apply a correction to the observed values of H/M, because the deflections do not follow the inverse-cube law of a simple dipole. These corrections are called distribution-coefficients, and are designated by the letters P and Q. Not considering induction, the constant used in the deflections is

$$C = 2/r^3(1 + P/r^2 + Q/r^4)$$

P and Q are functions of the pole-distances of the magnets. Assuming that the geometrical lengths of the magnets are in the same ratio as the pole-distances, as confirmed by experience, P is zero when the ratio (k) is 0.8165, and Q is zero when the ratio is 0.4667.

In designing instruments of precision, a sound principle is to make all corrections as small as possible. In the series-expression for the constant above, we would naturally make P zero. However, in most magnetometers of recent construction, Q is made zero, making the correction for distribution as large as possible, instead of as small as possible, in direct violation of our principle of design.

We shall estimate the effects of distribution in the form of corrections to H as derived from the deflection-observations, taking as a concrete case Cook magnetometer No. 40 (India Survey type) of the United States Coast and Geodetic Survey. This magnetometer has a "long" magnet 9.28 cm long, and for regular use a "short" magnet 4.32 cm long, thus making Q zero. The nominal deflection-distances are 30 and 40 cm. In this case the corrections would be 400γ and 228γ, respectively, for H computed from deflections, 17900γ and 18072γ for deflection-distances 30 cm and 40 cm, the true H being 18300γ.

Now suppose P is made zero, in which case the length of the short magnet would be 7.58 cm. Then the corrections would be -23γ and -7γ, respectively, for H computed from deflections, 18323γ and 18307γ for deflection-distances 30 cm and 40 cm, the true H being 18300γ. Note the decrease in the corrections.

Let us go further in our effort to eliminate the distribution-corrections. Let ℓ_a be the pole-distance of the long magnet, which is given and, in general, is five-twelfths of the geometrical length of the magnet. Let k be the ratio of the pole-distances. The distribution-effect is zero when

$$P/r^2 + Q/r^4 = 0$$

in which $P = \ell_a^2 (2 - 3k^2)$ and $Q = \ell_a^4 (3 - 15k^2 + 45/8\ k^4)$. Solving for k

$$k^2 = (1/45)\ \ell_a^2\ [S - \sqrt{(S^2 - T)}]$$

in which $S = 12(5l_a^2 + r^2)$ and $T = 360\ \ell_a^2\ (3l_a^2 + 2r^2)$. This equation can be solved for all distances ordinarily used on horizontal-intensity magnetometers, that is, from 20 to 50 cm. Thus, for a given deflection-distance r, it is possible to make two magnets of such lengths as to eliminate the correction for distribution. If L_a is the length of the long magnet, the length of the short magnet will be kL_a.

Choosing 30 cm as the nominal deflection-distance for zero-distribution effect, k is 0.80183, and the lengths of the magnets would be 9.28 and 7.44 cm. Using the exact deflection-distances of magnetometer 40, namely, 29.992 and 39.984 cm, the corrections for H computed from deflections, 18300γ and 18305γ, would be 0γ and -5γ, the true H being 18300γ.

We have now reduced the distribution-correction to zero for the distance 30 cm and to -5γ for the distance 40 cm. It is to be noticed that, when H/M is combined with HM from oscillations, the -5γ correction at 40 cm would be cut in half, so that the final correction at 40 cm would be only 2.5γ, which is the limit of accuracy possible with magnetometers, say one part in 10,000. Thus, in conformity with the principle of eliminating corrections, our aim would be practically attained.

The elimination of corrections is important not merely for obtaining correct calibrations. There is still the problem of reconciling measurements of H from magnetometers with those derived from electromagnetic instruments. For this purpose, the elimination of corrections is of the greatest importance.

U. S. Coast and Geodetic Survey,
Washington, D. C.

ON THE IONIZATION OF THE F_2-REGION

W. M. Goodall

(Abstract)

Monthly average values of the midday F_2-region critical frequencies obtained at Huancayo (Peru), Watheroo (Western Australia), and Washington, D. C., and Deal, New Jersey, during 1932 to 1937 are correlated with a smoothed value of the relative sunspot-number. Each month is treated separately. It is shown that for Washington and Deal the data indicate a direct correlation between smoothed sunspot-numbers and critical frequencies. While the data for Western Australia and Peru are not as complete, these are likewise consistent with a solar effect. Using the correlation-curves, the values of the critical frequencies normally to be expected for constant sunspot-numbers can be obtained for the different months.

Plotting these values as curves, it is shown that there are tendencies for both seasonal and annual effects. Thus for both Washington and Watheroo there is a tendency for a minimum to occur during local summer which is a seasonal effect. On the other hand, for Watheroo there is a somewhat broader tendency for a maximum to occur during the same months as at Washington, which is an annual effect since these two locations are in opposite hemispheres.

Comparison between the curves of expected critical frequencies and curves of Sun's zenith angle and of virtual height suggest as a possibility that the apparent annual effect may be due

to variations with latitude or general climate which cannot be eliminated without data from more locations.

[The complete paper has been submitted to the Institute of Radio Engineers for publication in the Proceedings of that body.]

Bell Telephone Laboratories,
Deal, New Jersey

A STUDY OF SUDDEN DISTURBANCES OF THE IONOSPHERE

J. H. Dellinger

Research is proceeding on a wide front in the cosmic sciences on a phenomenon which was unknown two years ago. The phenomenon is a sudden and short-lived increase of ionization of a part of the ionosphere, manifesting itself by perturbations in radio transmission, terrestrial magnetism, and earth-currents.

Whenever the phenomenon occurs, it is most intense in that region of the Earth where the Sun's radiation is perpendicular and diminishes to zero at the outer edge of the illuminated hemisphere. Its onset usually occurs within a minute, and is simultaneous throughout the hemisphere affected. Its various effects begin simultaneously, and last from about ten minutes to several hours, the occurrences of greater intensity in general producing effects of longer duration. The effects include the sudden blotting out of high-frequency radio sky-wave transmission, sudden changes in low-frequency atmospherics, sudden changes in terrestrial-magnetic intensities, and sudden changes in earth-currents. The effects are markedly different from other types of changes in these quantities. They are more intense where it is noon than other times of day, and are more intense in equatorial regions than in higher latitudes. The radio effects are very large, indicating that the ionospheric changes producing them are intense ones.

The phenomenon has occurred 118 times in the past two years and at 59 of these times a solar eruption was observed to occur simultaneously with the sudden disturbance of the ionosphere. It is believed to be demonstrated that some solar eruptions emit radiation of such wave-length as to produce intense ionization of the ionosphere below the E-layer. The phenomenon is known to be localized there, from the radio characteristics of the effect. The occurrence of visible light along with the ultra-violet radiation producing this effect is fortuitous.

The current studies of the effect give every promise of contributing extensively to knowledge of the nature of the ionosphere, the processes of radio wave-transmission, the mechanisms of terrestrial magnetism, and the phenomena occurring in the Sun.

National Bureau of Standards,
Washington, D. C.

AN INVESTIGATION OF THE RELATION BETWEEN BRIGHT CHROMOSPHERIC ERUPTIONS AND FADE-OUTS OF HIGH-FREQUENCY RADIO TRANSMISSION

R. S. Richardson

In October, 1935, Dr. J. H. Dellinger of the National Bureau of Standards described some sudden and remarkable fade-outs of high-frequency radio transmissions, affecting the daylight-side of the Earth and lasting for about 15 minutes each. He suggested that the fade-outs might be connected with solar eruptions and urged that special efforts be made to observe the Sun continuously to see if any unusual sunspot-activity occurred at the time of the next fade-out, which Dr. Dellinger believed might be expected after an interval of about 54 days.

An examination of the hydrogen and calcium spectroheliograms taken at Mount Wilson as part of the routine solar work showed that on three occasions bright chromospheric eruptions had been photographed within a few minutes of the radio fade-outs reported by Dr. Dellinger. Spectroheliograms had not been taken at the time two other fade-outs were observed. This agreement was so striking that it was decided to make special observations for several days before and after the date of the next predicted disturbance of radio transmission.

As already implied, one of the most curious features connected with the first four fade-outs was that they occurred at intervals of 53.4, 55.1, and 55.4 days, the mean being 54.5 days. This interval is twice the synodic time of solar rotation in latitude 16°, although the agreement may be only fortuitous. The first observing program was accordingly set for the latter part of October, 1935. An eruption of moderate intensity was photographed on October 24, 54.9 days after the preceding fade-out and eruption. On October 10 the National Bureau of Standards noted a general improvement in radio transmission on the higher frequencies, which continued until October 21 to 23, when the upper limit of frequency reached the highest value they had ever observed. On October 24, 1936, however, the upper limit dropped to half its value on the preceding days, and then on October 25 returned to its previous high value.

A repetition of the phenomenon was anticipated about the middle of December. A brilliant eruption took place on December 16, 53.0 days after October 24. No immediate report of a fade-out came to our attention, so that at first it was believed that this constituted an outstanding example of an outburst of major importance with no accompanying disturbance in radio transmission. Just recently, however, we have been informed of a fade-out that occurred within five minutes of the exposure on which the eruption could first be discerned, so that there was no break in the series as previously stated by the writer.

The next disturbance was experienced on February 14, 1937, when a wide-spread fade-out began at $15^h\ 18^m$ and lasted from 20 minutes to five hours, depending upon the frequency. Clouds prevented observations at Mount Wilson, but the Huancayo Magnetic Observatory of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington reported an eruption to be already in progress when they started their regular spectrohelioscopic observations at $15^h\ 30^m$.

Another fade-out and a bright eruption took place 54.1 days later, on April 8, and again on June 3, after an interval of 56.0 days. Although a minor fade-out was noted 53.0 days later, on July 26, the cycle evidently ended on June 3; at least the important disturbances of radio reported since then have not been in accordance with any simple and obvious law.

The observing program in October and December, 1935, and April, 1936, consisted simply in taking hydrogen spectroheliograms about every five minutes, unless interrupted by clouds or instrumental adjustments. Beginning in May, Dr. Seth B. Nicholson installed a camera adapted to take spectroheliograms automatically on 35-mm motion-picture film. The interval between exposures is ordinarily about four minutes, while the actual time required for the image to pass across the slit and thus complete the exposure is about 50 seconds. The machine is started soon after sunrise and operates continuously with very little attention until shut off about an hour before sunset. Hence, we have nearly complete records of the appearance of the Sun on all clear days at Mount Wilson since May, 1936. Sufficient data now exist to make a discussion of the material worth while.

A comparison of the radio fade-outs from April, 1934, to February, 1937, with the chromospheric eruptions photographed at Mount Wilson during that interval, reveals 34 coincidences so close that the probability of a relation between the two seems very strong. Other close coincidences have been observed at Greenwich, but only our own material will be discussed in detail here.

In 14 cases, the time when an eruption was first seen agrees to within two minutes or less with the time when the fade-out began. In all 14 cases solar observations had been made shortly before the fade-out occurred, the longest interval being ten minutes. If an eruption and a fade-out were actually observed to begin simultaneously, it would seem highly probable that energy emitted from the solar eruption with the velocity of light is the direct cause of the fade-out. The evidence to this effect is particularly strong for the disturbance on April 8, 1936. A spectroheliogram taken at $16^h\ 22^m$ GMT was quite normal. The next plate taken at $16^h\ 47^m$ showed that an unusually brilliant eruption had in the meantime occurred over a large spot-group near the central meridian. From the appearance of the bright flocculi and from previous knowledge of such eruptions it was estimated that the outburst began only a few minutes before the exposure was made. This estimate was confirmed later by a statement from the Huancayo Magnetic Observatory in Peru. The observers at this station witnessed the eruption with the spectrohelioscope, noting the first signs of activity at $16^h\ 45^m$. A major fade-out was experienced at $16^h\ 46^m$, which lasted from 15 to 30 minutes for various radio frequencies.

Twelve of the eruptions have apparently preceded the fade-out by from four to 17 minutes. The best example was on August 30, 1935. A sudden fade-out took place at $23^h\ 20^m$. Examination of a series of exposures taken every four minutes from $22^h\ 30^m$ to $23^h\ 30^m$ indicates that the eruption started as early as $23^h\ 00^m$, and at $23^h\ 08^m$ had become very bright. Here at least 12 minutes seems to have elapsed between the time the eruption was well under way and the beginning of the fade-out.

For the eight remaining fade-outs, observations were not made until nine to 30 minutes after the radio disturbance began, when eruptions were found to be already in progress. It seems probable that earlier observations would have shown the eruption occurring slightly before, or at the time of, the fade-out. No fade-out is definitely known to have preceded an eruption with which it was obviously connected.

Disturbances of the Earth's magnetic field and chromospheric eruptions occurred simultaneously with the radio fade-outs of November 28, 1934, February 14, April 8, November 8, 24, 26, 27, and December 24, 1936. The disturbances of the Earth's field as recorded at Mount Wilson all consist of a sudden decrease of about ten gammas in the horizontal intensity, accompanied by a change in declination of about 3' toward the east. These changes should not be confused with those characteristic of magnetic storms, which frequently last for several days with fluctuations in horizontal intensity and declination often 20 times greater than those accompanying a radio fade-out. There is evidence that magnetic storms may also be caused by chromospheric eruptions, but with an interval of the order of 26 hours between the eruption and the commencement of the storm.

Spectroheliograms of the bright flocculi associated with radio fade-outs have been studied to see if they differ in any way from eruptions which do not coincide with known geophysical phenomena. The only distinguishing feature readily discerned is that nearly all the eruptions producing fade-outs are much brighter than the average. This is shown in a striking way by the tabulation below of the number of fade-outs that have occurred in connection with chromospheric eruptions of different intensities. These intensities are simply eye-estimates made on the scale of 1 to 3 adopted by the International Astronomical Union.

Intensity	Number of eruptions	Coincident fade-outs	Per cent
1	118	15	12.7
2	33	8	24.2
3	12	11	91.7
Total	163	34	20.8

Only once has an eruption of great brightness failed to coincide with a radio fade-out, and even this case may not be an exception. On December 24, 1936, a flare of intensity 3 was photographed at $22^h 35^m$. At the same time our magnetograph recorded a sudden decrease in H of 3γ, but no perceptible change in D. Radio fade-outs took place at $22^h 05^m$ and $23^h 50^m$, but these were apparently produced by eruptions observed at nearly the same times.

Very little is known concerning the real brightness of the flocculi as it appears in $H\alpha$ and the H and K lines of calcium, with which our spectroheliograms are taken. Attempts have been made on several occasions to measure the intensity of bright hydrogen flocculi by photographic photometry. Observations are difficult to obtain due to the evanescent nature of the phenomenon. The flocculi that we have photographed on calibrated plates has been about 70 per cent as bright as the continuous spectrum within a few ångstroms of $H\alpha$. Recently, however, a series of exposures in $H\alpha$ was discovered taken in 1917 by Ferdinand Ellerman of the Mount Wilson Observatory, showing emissions from $H\alpha$ far more spectacular than any photographed later on. Unfortunately, the plate was not calibrated, but the continuous spectra on adjacent exposures overlaps in several places, and the overlap is only slightly denser than the bright hydrogen emission. In this particular case then, the flare as seen in $H\alpha$ was roughly almost twice as bright as the continuous spectrum nearby.

Of the 34 eruptions that have been observed at Mount Wilson in connection with radio fade-outs, 21 have occurred in the Southern Hemisphere in mean latitude 21°, and the remaining 13 have been in the Northern Hemisphere in mean latitude 20°. The mean distance of the 34 eruptions from the center of the Sun's disc is 0.74; the mean distance of the 149 bright eruptions observed during the same interval is 0.67. So far, the eruptions have shown no definite tendency to favor a particular region in heliographic longitude. It has long been known, however, that very large magnetic storms are more frequent when large active spot-groups are near the central meridian. This circumstance is naturally explained if we may assume that radio fade-outs are caused by radiation and magnetic storms by charged particles ejected radially from sunspots with a high velocity. Radiant energy would reach the Earth regardless of where it originated on the disc, but a stream of charged particles would not be likely to encounter the Earth unless ejected from a spot near the central meridian.

The radiation producing the fade-outs seems undoubtedly to come from the outbursts that show so conspicuously on hydrogen and calcium spectroheliograms. A natural assumption would be to suppose that a small area on the Sun, at a high temperature, emits large quantities of black-body radiation of high frequency; but direct observational evidence throws considerable doubt on this assumption.

For many years the spectroheliograms at Mount Wilson were taken with two slits set about five cm apart--one over the Hα or the K2 line, the other over some part of the continuous spectrum. Two images are thus obtained simultaneously: A spectroheliogram in the light of Hα or K2, and a monochromatic image resembling a direct photograph of the Sun. In the course of the routine solar observing we have by chance photographed many bright eruptions. If these eruptions are associated with black-body radiation of high temperature, they should also show conspicuously on the monochromatic images taken at the same time. An inspection of many plates showing strong eruptions in Hα or K2 fails to show any trace of a corresponding record on the images made with the continuous spectrum.

The question naturally arises why certain eruptions produce radio fade-outs while others do not. It is suggested that possibly the condition of the ionosphere, in addition to radiant energy from the Sun, may be a factor in determining whether or not a fade-out of high-frequency radio transmission occurs.

Mount Wilson Observatory,
Carnegie Institution of Washington,
Pasadena, California

RADIO FADE-OUTS ASSOCIATED WITH BRIGHT CHROMOSPHERIC ERUPTIONS

L. V. Berkner and H. W. Wells

(Abstract)

The radio fade-out effect reported by Dellinger and Jouaust can be studied from the echo-disappearance observed on the ionospheric traces during such disturbances. Twenty months of continuous data from the Huancayo Magnetic Observatory, and five months of data from the Watheroo Magnetic Observatory, both of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, are analyzed. The data presented are in more quantitative form than heretofore available. The results are in general agreement with the points made by Dellinger in his discussion of this effect, except as concerns the periodicity of the effect. Fade-outs occur only in the sunlit hemisphere, with the most intense effect within about 30° of the sub-solar point. The correlation between monthly numbers of fade-outs and sunspots is $+0.53 \pm 0.1$ for the data from Huancayo. The evidence presented appears to support Dellinger's hypothesis of the origin of these effects in the bright chromospheric eruptions associated with sunspot-areas, and many coincidences have been established. There is a strong tendency for fade-outs to be grouped; when one appears it is often followed by a series of fade-outs which occur around the Earth in the sunlit hemisphere. The commencement of a fade-out is essentially coincident at all stations within the probable limit of time-determination. The fade-out is short--more than 60 per cent of fade-outs are less than 15 minutes long. The data are not yet sufficient to establish any recurrence or quasi-recurrence tendency. The effect appears to be an absorption of the radio signal below 110 km. Taking into account the published evidence of the Bureau, and Best, Ratcliffe, and Wilkes, on long waves, it is seen that the lower limit of the effect must extend down to about 60 km. Therefore it may be supposed that the absorption occurs in the region of high collisional frequency between 60 and 100 km because of the increase of ionization in this region arising from absorption of ultra-violet radiation from bright chromospheric eruptions. The higher ionospheric regions are apparently unaffected, indicating no appreciable absorption of the radiation, causing the fade-out, in these regions.

[For a more complete account of this paper, see "Study of radio fade-outs" by L. V. Berkner and H. W. Wells (Terr. Mag., v. 42, pp. 185-196, 1937).]

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Washington, D. C.

TERRESTRIAL EFFECTS ASSOCIATED WITH BRIGHT CHROMOSPHERIC ERUPTIONS

A. G. McNish

Over half a century ago Professor C. A. Young called attention to simultaneous occurrence of brightening of H-alpha light in regions of sunspots and certain disturbances of terrestrial magnetism. He surmised that the terrestrial effects were caused by the solar activity and that the active agent connecting the two phenomena was propagated from the Sun to the Earth with the velocity of light. This important observation and suggestion were not taken up by other investigators for many years. Students of the Earth's magnetism found that the great perturbations of terrestrial magnetism--called magnetic storms--were related to solar activity in a statistical sense only. Attempts to associate magnetic storms with central-meridian passages of sunspots indicated a lag of a whole day and more between the solar and terrestrial phenomena.

A fresh impetus was given this study by Dr. J. H. Dellinger [see 1 of references at end of paper] of the National Bureau of Standards, who announced that sudden fade-outs of radio signals reflected from the ionosphere had been observed which exhibited an apparent recurrence-tendency of about 54 days--roughly twice the period of solar rotation. At his request, special solar observations were made at the Mount Wilson Observatory of the Carnegie Institution of Washington at times when fade-outs were expected to ascertain if any visible solar effect could be associated with them. Examination of old spectroheliograms revealed that several of the fade-outs reported by Dr. Dellinger had been accompanied by bright chromospheric eruptions corresponding closely in time.

Further evidence on this apparent connection was supplied by an unusually intense chromospheric eruption [2] revealed on the photographic plate made at Mount Wilson at 16^h 47^m GMT, April 8, 1936. Reports from radio operators scattered over the sunlit hemisphere of the Earth revealed that a wide-spread fade-out of radio signals also had occurred, while examination of magnetic records made at Mount Wilson and at Cheltenham, Maryland, disclosed a sudden change in the Earth's magnetism.

Routine observations with the spectrohelioscope were in progress at the Huancayo Observatory of the Carnegie Institution's Department of Terrestrial Magnetism at this time [3]. The observer on duty noticed a remarkable brightening of the H-alpha light in the region of a large sunspot, beginning at 16^h 45^m GMT. This eruption was accompanied by certain terrestrial phenomena as shown in Figure 1. These spectroheliograms made at Mount Wilson before the eruption, while the eruption was at its maximum, and after the eruption had subsided show the brightening of the sunspot, although high contrast of the negatives used permit little discrimination regarding intensity. The observers at Huancayo reported that "from the viewpoint of extent and intensity" this was the most spectacular eruption which had been witnessed at the Observatory since beginning routine observations with the spectrohelioscope a year before.

Ignorant of the solar fireworks in progress, the radio operator at the station, who was engaged at the time in making measurements on the ionosphere, found it impossible to receive reflections, and began to search for defects in his equipment. Finding none, observations were resumed. The disappearance of these echoes and their subsequent return 55 minutes later is illustrated at the top of Figure 1. The sudden changes in the Earth's magnetism and in the earth-currents which are continually registered at the Observatory are conspicuous in the records at the bottom of Figure 1.

This association of events strongly suggests a close relationship between bright chromospheric eruptions and phenomena of the ionosphere and terrestrial magnetism. Extraordinarily bright chromospheric eruptions were observed August 25 and November 6, 1936, also, and were found to be accompanied by similar phenomena. Although many chromospheric eruptions have been observed during the past few years, a number of which have been accompanied by radio fade-outs and a still smaller number by magnetic effects [4], the effects accompanying the eruptions of April 8, August 25, and November 6, 1936, have been selected for special study because of the magnitude of the effects involved.

It is possible to demonstrate from the records of many magnetic observatories, as shown in Figure 2, that the magnetic changes are distinct in type from any of those which have been previously recognized. They are confined to the daylight portions of the Earth. The heavy arrows in Figure 2 show the currents flowing in the ionosphere which would produce the observed changes at the various points while the light arrows show the currents necessary to produce the diurnal-variation departures existing when the solar flare occurred. The light arrows obviously define for the Northern Hemisphere the vortex of currents flowing in the ionosphere which, according to the Stewart-Schuster theory, give rise to the diurnal variations of terrestrial magnetism. This current-vortex is approximately centered on the noon-meridian, as indicated by the sub-solar point. The current-vectors of the solar-flare disturbance are nearly proportional and parallel to them. No arrows are shown for San Juan as the departures were immeasurably small--the center of the current-vortex being approximately over that Observatory. Insufficient data are available to define the current-vortex in the Southern Hemisphere. Except for the slight effect at Honolulu, no effects could be discerned for observatories more than about 70° from the sub-solar point.

Figure 3 shows the current-system for the disturbance of August 25, occurring when the Sun was much farther west. In this case strong effects were observed at Sitka, Meanook, and Honolulu, while no effect could be detected at San Miguel and Coimbra--over 70° from the sub-solar point. The current-vortex in the Southern Hemisphere is suggested by the directions of the arrows for Pilar and Vassouras.

A similar system of arrows for the disturbance of April 8 is shown in Figure 4. This distribution exhibits features of both disturbances on August 25 and November 6. Special attention should be called to the apparently anomalous direction of the arrows for Teoloyucan. However, since both arrows point in the same general direction, it is concluded that currents of the disturbance follow the diurnal-variation currents and do not constitute a different mode of circulation.

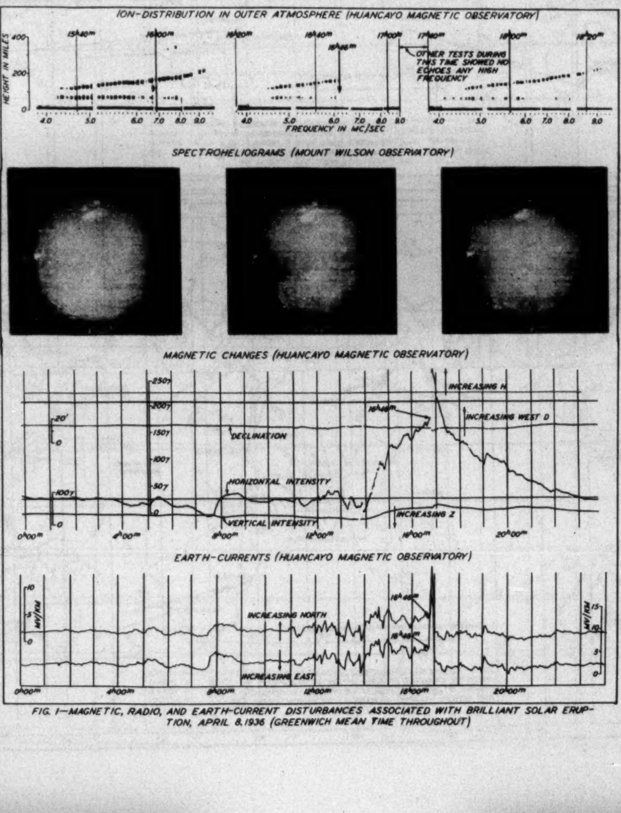

FIG. 1—MAGNETIC, RADIO, AND EARTH-CURRENT DISTURBANCES ASSOCIATED WITH BRILLIANT SOLAR ERUPTION, APRIL 8, 1936 (GREENWICH MEAN TIME THROUGHOUT)

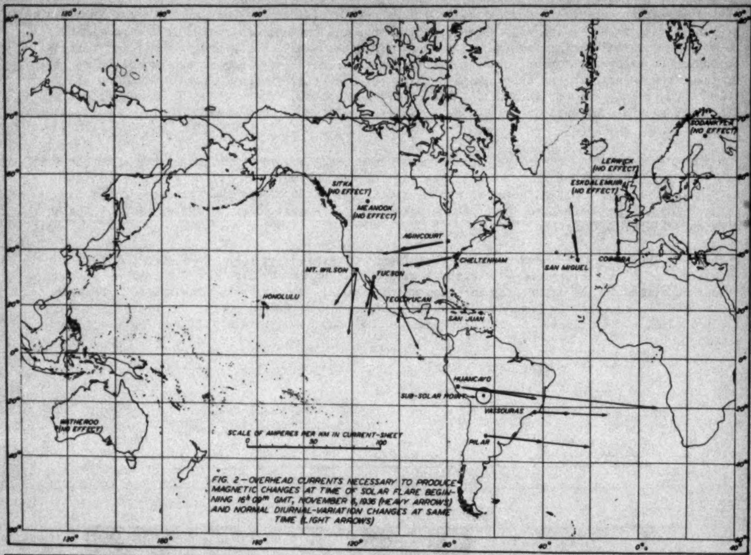
SODANKYLÄ (NO EFFECT)
LERWICK (NO EFFECT)
ESKDALEMUIR (NO EFFECT)
SITKA (NO EFFECT)
MEANOOK (NO EFFECT)
AGINCOURT
CHELTENHAM
SAN MIGUEL
COIMBRA
MT. WILSON
TUCSON
HONOLULU
TEOLOYUCAN
SAN JUAN
HUANCAYO
SUB-SOLAR POINT
VASSOURAS
PILAR
WATHEROO (NO EFFECT)
SCALE OF AMPERES PER KM IN CURRENT-SHEET
0
50
100
120°
160°
160°
120°
80°
40°
0°
40°

FIG. 2—OVERHEAD CURRENTS NECESSARY TO PRODUCE MAGNETIC CHANGES AT TIME OF SOLAR FLARE BEGINNING $16^h 09^m$ GMT, NOVEMBER 8, 1936 (HEAVY ARROWS) AND NORMAL DIURNAL-VARIATION CHANGES AT SAME TIME (LIGHT ARROWS)

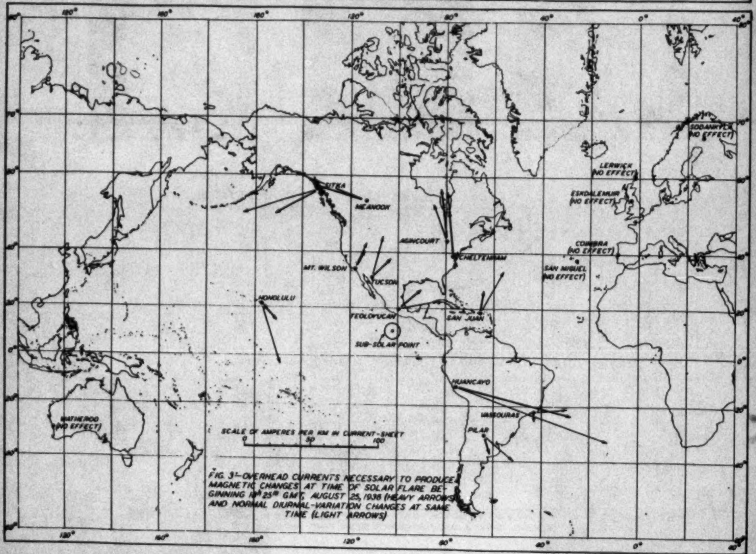
SODANKYLÄ (NO EFFECT)
LERWICK (NO EFFECT)
ESKDALEMUIR (NO EFFECT)
SITKA
MEANOOK
AGINCOURT
CHELTENHAM
COIMBRA (NO EFFECT)
SAN MIGUEL (NO EFFECT)
MT. WILSON
TUCSON
HONOLULU
TEOLOYUCAN
SAN JUAN
SUB-SOLAR POINT
HUANCAYO
VASSOURAS
PILAR
WATHEROO (NO EFFECT)
SCALE OF AMPERES PER KM IN CURRENT-SHEET
0
50
100
120°
160°
160°
120°
80°
40°
0°
40°

FIG. 3—OVERHEAD CURRENTS NECESSARY TO PRODUCE MAGNETIC CHANGES AT TIME OF SOLAR FLARE BEGINNING $18^h 25^m$ GMT, AUGUST 25, 1936 (HEAVY ARROWS) AND NORMAL DIURNAL-VARIATION CHANGES AT SAME TIME (LIGHT ARROWS)

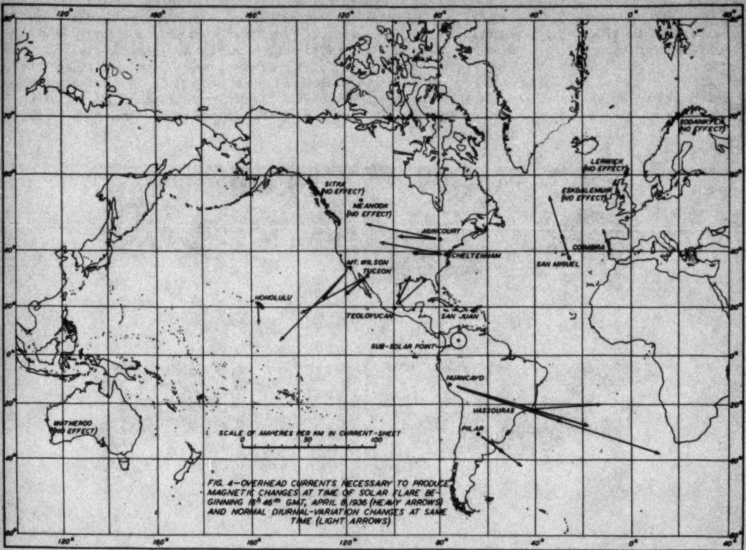
120°
160°
160°
120°
80°
40°
0°
40°
SITKA (NO EFFECT)
MEANOOK (NO EFFECT)
AGINCOURT
CHELTENHAM
MT. WILSON
TUCSON
HONOLULU
TEOLOYUCAN
SAN JUAN
SUB-SOLAR POINT
HUANCAYO
VASSOURAS
PILAR
WATHEROO (NO EFFECT)
SODANKYLÄ (NO EFFECT)
LERWICK (NO EFFECT)
ESKDALEMUIR (NO EFFECT)
COIMBRA
SAN MIGUEL
SCALE OF AMPERES PER KM IN CURRENT-SHEET
0
50
100

FIG. 4—OVERHEAD CURRENTS NECESSARY TO PRODUCE MAGNETIC CHANGES AT TIME OF SOLAR FLARE BEGINNING $15^h 46^m$ GMT, APRIL 8, 1936 (HEAVY ARROWS) AND NORMAL DIURNAL-VARIATION CHANGES AT SAME TIME (LIGHT ARROWS)

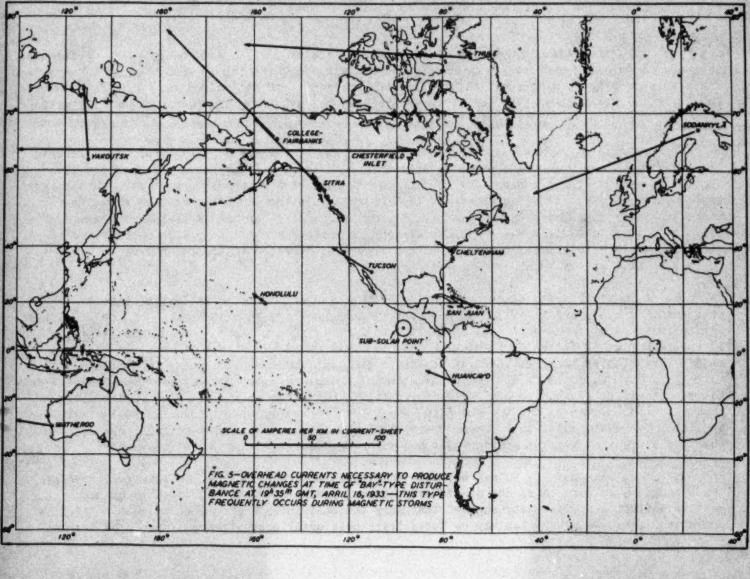
120°
160°
160°
120°
80°
40°
0°
40°
THULE
COLLEGE-FAIRBANKS
CHESTERFIELD INLET
YAKOUTSK
SITKA
SODANKYLÄ
CHELTENHAM
TUCSON
HONOLULU
SAN JUAN
SUB-SOLAR POINT
HUANCAYO
WATHEROO
SCALE OF AMPERES PER KM IN CURRENT-SHEET
0
50
100

FIG. 5—OVERHEAD CURRENTS NECESSARY TO PRODUCE MAGNETIC CHANGES AT TIME OF "BAY"-TYPE DISTURBANCE AT $19^h 35^m$ GMT, ARRIL 16, 1933—THIS TYPE FREQUENTLY OCCURS DURING MAGNETIC STORMS

The difference between the type of magnetic disturbance associated with a solar flare and the types observed during magnetic storms is brought out by Figure 5, showing the currents necessary to produce a "bay"-disturbance. These bays frequently occur simultaneously all over the Earth, and are most strongly manifested on the night side. During a bay the strongest currents flow near the auroral zone and are usually more intense than those deduced for solar-flare disturbances. Furthermore, while a solar-flare disturbance lasts for about an hour, the perturbations occurring during a magnetic storm usually continue to disturb the field for several days.

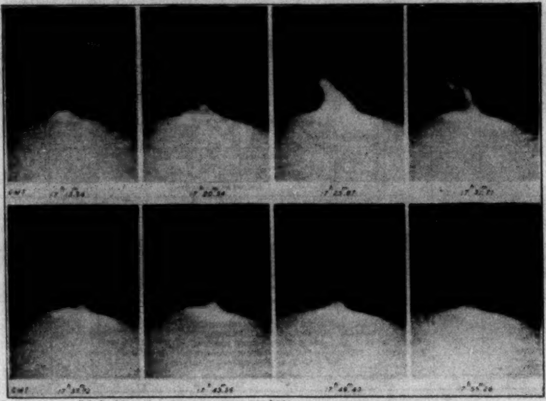

FIG. 6—BRIGHT CHROMOSPHERIC ERUPTION ON LIMB OF SUN AUGUST 8, 1936
[PHOTOGRAPHED AT McMATH-HULBERT SOLAR OBSERVATORY]

The radio fade-out accompanying these flares admits of obvious explanation--the creation at the base of or below the E-layer of dense and short-lived ionization in which the radio waves are absorbed owing to high frequency of collision between ions and molecules. When this absorbing layer has disappeared, the higher layers seem to be in their original condition, indicating that they had not been appreciably affected.

Such increased ionization in the lower part of the ionosphere would increase the electric conductivity of the region and permit greater currents to flow. The necessary electromotive forces for driving these currents--according to the Stewart-Schuster theory of the diurnal variations--arises through tidal movements of the atmosphere in the Earth's permanent magnetic field. Since the lower ionosphere is most favorable for the operation of the mechanism of the Stewart-Schuster theory, and since radio effects clearly indicate that the ionization-changes during a solar flare occur there, the magnetic changes described here furnish corroborative evidence in support of that theory.

The ratio of magnetic changes occurring at the time of the eruption to the magnetic departures of the diurnal variation at the same time may be considered a measure of the intensity of the ionization produced. Since the return to normal is very rapid, the rate of recombination of the ions must be extremely high, and since the maximum of the effect is attained sometimes within five minutes after brightening begins in the eruption, as in the case for April 8, the rate of ion-production must also be high. It may be supposed that the visible line-emission from the eruptions is accompanied by line-emission in the ultra-violet and emission in the ultra-violet continuum, and that these emissions cause the ionization which produces the terrestrial effects. The rapidity of the changes suggests that such radiations must be much more intense than the ultra-violet light ordinarily coming from the Sun.

It is not yet possible to say why some eruptions produce no noticeable effects, while others produce radio fade-outs, and others produce both radio fade-outs and magnetic changes. Subjective estimates of intensity suggest that only the most intense eruptions produce noticeable magnetic effects--a view which may be tentatively held until accurate measurements of intensities are available. The eruptive region need not be near the center of the Sun's disc to produce an effect--the eruption of August 25 was 0.96 of a radius from the center. Eruptions causing these effects may be different in nature from the familiar eruptive prominences. Figure 6 shows a photographic series of an eruption on August 8 taken at six-minute intervals. In this case the gas seems to fall back into the Sun and not continue off into space as usually happens for an eruptive prominence. This eruption was associated with a fade-out occurring at $17^h\ 25^m$ GMT--the time of greatest brightness. No magnetic effects could be detected. This eruption was of less extent and less intensity than the ones producing the effects discussed in this paper.

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[1] Phys. Rev., v. 48, p. 705, 1935.
[2] R. S. Richardson, Terr. Mag., v. 41, pp. 197-198, 1936.
[3] O. W. Torreson, W. E. Scott, and H. E. Stanton, Terr. Mag., v. 41, pp. 199-201, 1936.
[4] J. H. Dellinger, Terr. Mag., v. 42, pp. 49-53, 1937.

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WORLD-WIDE CHANGES IN POTENTIAL GRADIENT

G. R. Wait and John W. Mauchly

At the Edinburgh Assembly of the International Union of Geodesy and Geophysics, in the Association of Terrestrial Magnetism and Electricity, data for the years 1924 to 1934, inclusive, for Watheroo, Huancayo, and Ebro, were shown to suggest a world-wide change in potential gradient from year to year. Data for the year 1935 have now been added, and Figure 1 shows the percentage deviations of each station from its 12-year mean. The evidence for relationship can hardly be adjudged on the basis of such a graph, and this paper is concerned with a statistical analysis of the data. The records of other observatories have been examined, and in a general way they may be said to favor the hypothesis of a universal effect, but the present report will deal only with the three stations mentioned.

A word must be said as to the selection of the data. Watheroo, Huancayo, and Ebro were chosen as best situated to be free from disturbing effects, such as atmospheric pollution. Only data believed to be free from effects of pollution and thunder-storm were used in deriving monthly means, but not all months were used. The months of June, July, August, and September were selected as those in which the pollution- and thunder-storm effects would have the least influence at Watheroo and Huancayo. These same months were then used for Ebro. Each of the four months was given equal weight in deriving an "annual value" for each station.

The intercorrelations of the three series of 12 points each were then calculated, yielding

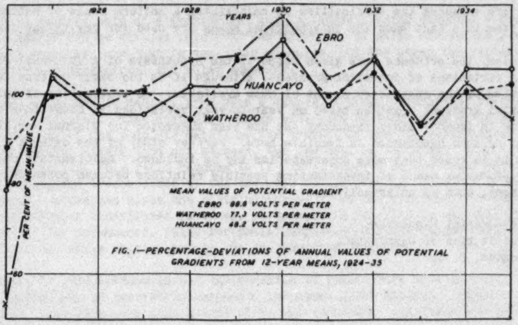

FIG. 1—PERCENTAGE-DEVIATIONS OF ANNUAL VALUES OF POTENTIAL GRADIENTS FROM 12-YEAR MEANS, 1924-35

the following correlation-determinant (E, W, and H indicating the Ebro, Watheroo, and Huancayo magnetic observatories, respectively):

$$z = \begin{array}{c|ccc|} & E & W & H \\ E & 1.000 & 0.882 & 0.862 \\ W & 0.882 & 1.000 & 0.839 \\ H & 0.862 & 0.839 & 1.000 \end{array} = 0.0509$$

The statistic, z, is more appropriate than a multiple correlation-coefficient for present purposes because it treats the three series symmetrically, while multiple correlation-methods require that one variate be designated as dependent upon the other two. If the value of z is zero, complete dependence among the variables is implied, while, if z is unity, complete independence is signified.

The value of the determinant is 0.0509 and the question as to its significance naturally arises. Spurious correlations may occur, in small samples especially, and obviously z will be subject to sampling errors. Fortunately, the distribution of z for normally distributed independent variates has recently been obtained by Wilks (Econometrica, v. 3, pp. 309-326, 1935), so that a significance-test is possible.

On the hypothesis that we are here dealing with three normally distributed, completely independent series, the chance that, in a set of 12 observations, we should obtain a value of z as low or lower than 0.0509 is roughly 1/200,000. Independence is thus seen to be quite unlikely if the conditions presupposed by this test have been fulfilled.

On this point, several remarks may be made. First, were the data selected from a larger body of data on the basis of the closeness of relationship displayed, the probability of independence could no longer be taken as 1/200,000. For instance, selecting three series from eight so as to achieve the lowest value of z would require that we multiply this fraction by 56, since there are 56 different sets of three series which might be chosen from eight. As such things are often judged, the new probability of about 1/3500 would still be accepted as favoring dependence. But in actual fact, as has been explained, the selection was not made in this way, but was based entirely upon *a priori* considerations.

In the second place, we have no knowledge as to whether or not the distribution is normal. This fact should not be construed as completely invalidating all applications to data of unknown distribution. To avoid any assumption concerning normal or other distributions, one may resort to rank correlation-methods. The determinant of rank correlation-coefficients is again the proper statistic, but its distribution has not yet been calculated.

In this connection, it is of interest to note the result of applying similar tests to magnetic data in which the universal effect is unquestioned, namely, the magnetic character-number, C. With many stations contributing daily values for 30 years, there is no difficulty in establishing the universal quality of C. But if we restrict ourselves to just the same months and years, for the three observatories used in the potential-gradient study, the value of z becomes 0.667, with a "probability of chance" of about 1/4. Since C is a subjective measure, frequent change of observers enhances the difficulties of maintaining a uniform scale of estimation. No troubles arise from this fact when the *international means* are used for *day-to-day* comparisons.

In our opinion, the evidence here given supports the hypothesis of a universal effect in the year-to-year variations of potential gradient, although it is too early to draw definite conclusions in view of the restricted amount of data available. An explanation of world-wide change in potential gradient might be based on year-to-year variations in conditions of the upper atmosphere or in thunder-storm frequency--as has been suggested for diurnal variations--but no adequate test of such hypotheses is feasible here. Further study of the data is now being carried on, and it is hoped that more observatories may be included. Multivariate correlation-methods offer a promising means of investigating possible relations between potential gradient and other phenomena, such as solar activity.

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A NEW APPROACH TO THE STUDY OF TERRESTRIAL-SOLAR RELATIONSHIPS

John W. Mauchly

That statistical procedures are not only appropriate but expeditious to the point of necessity for furthering our knowledge concerning the relations between solar and terrestrial phenomena, need not be argued here. In so far as the technique of correlation has been employed for this purpose, it is notable that only the simple correlation-coefficients are generally calculated. Such restriction implies the hope of discovering one single, directly observable, solar phenomenon which shall be closely connected with one single, directly observable, terrestrial phenomenon, and indicates slight interest in more complicated relationships.

Multiple and partial correlation-methods seem rather to have been avoided. Several reasons for this may suggest themselves, namely, lack of parallel series of data, increased labor of computation, difficulty in interpreting the results, etc. Aside from lack of data, the most important reason has very likely been that it was not obvious that any new information would be gained by such methods.

At this point, a quotation from R. A. Fisher seems apt: "In most kinds of experimentation, however, the possibilities of obtaining greatly increased precision from comparatively simple supplementary observations are almost entirely unexplored, and, indeed, in many fields the possibility of making a critically valid use of such observations is scarcely recognized." The term "experimentation" is here broad enough to include the study of solar-terrestrial relationships, and it seems to the author that Fisher's remark has force when so applied.

Recent advances in the mathematical statistics of multivariate correlation-analysis offer a new approach to this old problem. For illustration of the way in which the new technique may be applied, some preliminary work utilizing six series of 50 terms each is presented. These are the six-month means for the years 1910 to 1934, inclusive, for the following: u_1, the magnetic activity measure of Bartels; C, the international magnetic character-number; P, the areas of solar prominences (Zurich); F_R, the calcium flocculi in the neighborhood of sunspots (Ebro); F_c, the calcium flocculi, classified as "c" by Ebro; and F_{cd}, the calcium flocculi, classified as "cd" by Ebro. The last three are measures of the frequency of the flocculi to which they refer. They were used in this study for several reasons: (1) They form a complete 25-year sequence of solar observations not previously, so far as the author knows, studied by correlation-methods; (2) F_R is claimed by the Ebro Observatory to be a better measure of solar activity than the usual sunspot-number, R; (3) F_c and F_{cd} are not highly correlated with other solar measures, so that one may suspect that they measure a different phase of solar activity. The simple correlations between these measures are as follows:

u_1					
0.599	C				
0.791	0.367	P			
0.807	0.448	0.847	F_R		
0.507	0.113	0.452	0.255	F_c	
0.623	0.218	0.668	0.559	0.854	F_{cd}

This is in reality half of a symmetrical matrix, whose leading diagonal elements are unity. The complete matrix can be divided into four sub-matrices, of which one refers just to the terrestrial-magnetic measures, one just to the solar measures, and the other two represent intercorrelations between the terrestrial and solar measures.

Wilks has shown how to derive, from such a matrix, a single measure of correlation between the two sets of variates. This statistic, which will here be denoted by z, is computed by dividing the determinant of the complete matrix by the product of the two determinants which involve just the correlations within, and not between, the two sets of variates. When either set contains just one variate, this ratio reduces to $(1 - R^2)$, where R is the usual multiple correlation-coefficient. Complete independence of the two sets of variates is indicated by values of z approaching unity. Wilks has given the distribution of z, on the hypothesis of independence between sets of normally distributed variates, so that it is possible to use this statistic to make a sensitive test for dependence, valid for small samples as well as large. This test will be applied, not to the above matrix, but to one derived from it later.

Dependence or independence is not the question at issue; work such as that of Bartels on the 27-day periodicity in terrestrial-magnetic phenomena gives abundant evidence of solar influence. However, this same work drew attention to two important, and perhaps related, facts: (1)

Strong magnetic activity, with the 27-day periodicity very prominent, sometimes occurs without corresponding fluctuations in sunspot-numbers; (2) serious discrepancies may arise between u_1 and C. When we consider the way in which these two magnetic activity-indices are derived, we see that there is no necessity for the two to agree at all times. We may dismiss the matter there, or we may consciously adopt one or the other of the following hypotheses:

(1) The single-factor hypothesis--In so far as C and u_1 measure anything of physical significance, they measure the same thing, but C is a less reliable measure, affected by larger random errors.

(2) The multiple-factor hypothesis--C and u_1 are affected to varying degrees by two or more physical influences, but not in the same proportions. (Of course, the presence of some "random element" in each is still assumed.)

If hypothesis (2) is adopted, it is then our business to attempt identification of the separate influences. But before embarking upon this difficult task, or before adopting hypothesis (2) at all, we must first show that (1) has failed.

Here again we receive aid from the recent work in multivariate analysis. Hotelling has begun exploring relations between sets of variates by what is known as "vector-correlation." It is difficult in a few words to do justice to this tool, but an explanation will be attempted in terms of the specific problem before us here.

We begin by seeking a linear combination of C and u_1, and a linear combination of the solar measures, such that the simple correlation-coefficient between these two linear functions will be a maximum. The functions thus found are called the first canonical variates, and the coefficient of correlation between them is known as the first canonical correlation. Having done this, we then determine two more linear functions, one of each set of variates, having zero-correlation with the first canonical variates, and having the maximum possible correlation with each other under these conditions. We have thereby found the second canonical variates, and the second canonical correlation. As many canonical variates and correlations may be found as there are variates in the smaller original set; in the present case, since the magnetic variates, u_1 and C, are only two in number, the following two canonical correlations and the corresponding variates exhaust the possibilities:

	u_1	C	P	F_R	F_c	F_{cd}
$r_1 = 0.893$	1.00	-0.18	0.27	1.00	0.88	-0.58
$r_2 = 0.213$	-0.47	1.00	-0.58	1.00	-0.54	-0.08

(The canonical variates are supposed to be adjusted to have unit standard-deviations, but to facilitate comparisons, the above are adjusted so as to have the largest coefficient in each set unity.)

One obvious result is the large relative weight of F_R in both of the canonical variates, apparently justifying the high regard in which Ebro holds this measure. But this could have been foreseen from the correlation-matrix. A more startling result is the fact that u_1 and C are given opposite signs in each case.

We now come to a most important point, namely, the significance of the canonical correlations. Hotelling has shown that, to a first approximation, these have the same standard deviation as an ordinary correlation-coefficient. Therefore, we may make a rough but simple test of the significance of the deviation of either of the above coefficients from zero by comparing them to the standard deviation, 1/7. The first is obviously significant, as we would expect. The second coefficient, 0.213, is only about 1.5 times the standard deviation of a zero-coefficient, and the evidence here is inconclusive. This is unfortunate, since it is on the basis of this evidence that we hope to discriminate between the single-factor hypothesis, (1), and the multiple-factor hypothesis, (2). When the second canonical correlation can be shown to be significantly non-zero, hypothesis (1) fails.

The degree of agreement achieved by the first canonical variates is portrayed graphically by a scatter- or dot-diagram of Figure 1, which incidentally shows that the relationship is not far from linear. A glance at the canonical variates plotted against time in Figure 2 warns of a serious statistical error. In testing the canonical correlations just now, it was assumed that we were dealing with 50 independent observations, whereas the presence of the 11-year cycle is quite obvious in this graph, so that high values tend to be followed by high values, and low by low. The proper remedy is to remove this trend, and deal with the deviations from the trend. In lieu of this treatment, partial correlation-coefficients have been computed, eliminating all

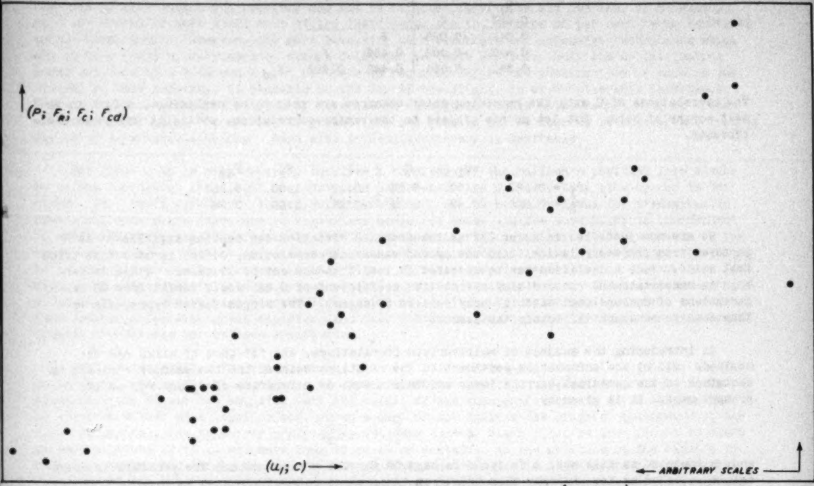

FIG. 1—SCATTER-DIAGRAM FIRST CANONICAL VARIATES ($r_1 = 0.893$)

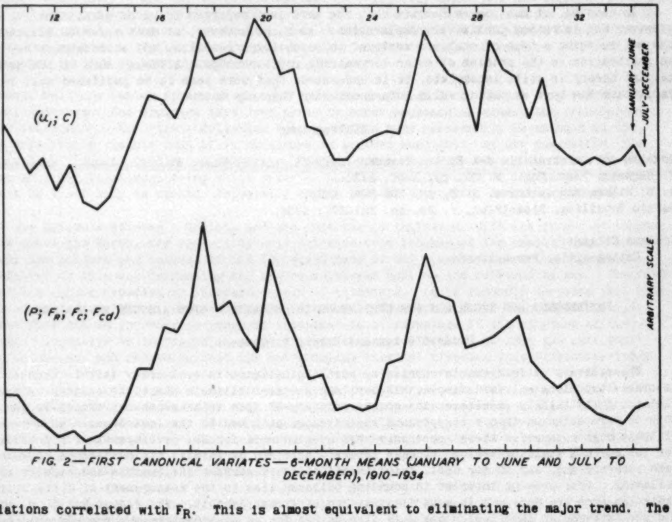

FIG. 2—FIRST CANONICAL VARIATES—6-MONTH MEANS (JANUARY TO JUNE AND JULY TO DECEMBER), 1910-1934

variations correlated with F_R. This is almost equivalent to eliminating the major trend. The partial correlation-coefficients form a new matrix as follows:

u_1				
0.450	C			
0.342	-0.028	P		
0.529	-0.002	0.459	F_c	
0.351	-0.044	0.442	0.888	F_{cd}

The correlations of C with the remaining solar measures are seen to be negligible, a fact in itself worthy of note. But let us now proceed to the vector-correlation, utilizing the above coefficients.

	u_1	C	P	F_c	F_{cd}
$r_1 = 0.583$	1.00	-0.53	0.19	1.00	-0.55
$r_2 = 0.325$	-0.59	1.00	-0.29	-1.00	0.38

We are now justified in using 1/7 as the standard deviation for testing significant departures from zero-correlation. And the second canonical correlation, 0.325, is more than twice that value. Such a deviation can be expected in less than one out of 30 cases. (This is perhaps an understatement--an ordinary correlation-coefficient of 0.325 would result from 50 observations of uncorrelated material only once in 50 cases.) The single-factor hypothesis is thus seen to be doubtful, to say the least.

In introducing the subject of multivariate correlations, the "z"-test of Wilks was described. All of the information pertinent to the relations between the two sets of variates is contained in the canonical correlations, and thus z must be a function of r_1 and r_2, in the present case. It is given by

$$z = (1 - r_1^2)\,(1 - r_2^2)$$

and, calculated in this way, z is found to be 0.59 for the present data. The probability of obtaining a value as low or lower than this from independent sets of variates is roughly 1/1700.

In closing, it must be emphasized that the work just reported is by no means final or conclusive, but is rather preliminary exploration. As such, however, it does serve to illustrate the way in which a type of analysis employed in psychology, genetics, and econometrics may find an application to the problem of solar-terrestrial relationships. Although much of the mathematical theory is still incomplete, it is understood that work soon to be published will further facilitate the task of making valid inferences with this new tool.

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INSTRUMENTS AND TECHNIQUE FOR CONTINUOUS TRIANGULATION UPON A SOUNDING-BALLOON

Brian O'Brien and Harold S. Stewart, Jr.

The recovery of instruments carried by sounding-balloons is ordinarily left to chance. In favorable locations as, for example, Missouri and southern Illinois where the country is open and flat and quite thickly populated, the chance recovery of such instruments may exceed 90 per cent with no more stimulus than a conspicuous reward-label attached to the instrument. As a result of these high recoveries there appears to have been no need for the development of a procedure for following a sounding-balloon to make recovery approach certainty, the difference between such recovery and, say 90 per cent, being insufficient to warrant the trouble and expense of following. (Our present interest in sounding-balloons lies in the measurement of ultra-violet radiation from the Sun, and in such fluctuations as it may exhibit. The aid of Dr. C. G. Abbot and the Smithsonian Institution has made it possible for us to undertake our present program.)

For such researches as involve, for example, recording meteorographs or telemeteorographs where the cost per instrument is moderate and many similar instruments can be made economically, the time between flight and recovery may not be of great importance and one can, if necessary, wait six months or more until most of the instruments are in, perhaps 50 per cent being recovered in the first month. However, for work involving more elaborate and expensive instruments which may be in a state of development, such a delay can be quite serious. Only one or two instruments are made at a time and a test of these is required before the construction of more is justified, so that recovery, if possible on the day of the flight, is of considerable importance. There are, moreover, certain types of observation at high altitudes which cannot well be transmitted by radio to a recorder on the ground, yet the results may be desired at once or the records may be of a perishable nature. Here also immediate recovery is desirable.

The first step in such recovery involves a knowledge of the balloon's position from minute to minute throughout its flight, so that this may be reported by radio to a pick-up car in the field. Were radio direction-finding sufficiently accurate it would be ideal for triangulation upon a balloon, since questions of visibility would not enter and the work might be independent of weather-conditions. Unfortunately existing methods of radio goniometry fall far short of the necessary accuracy, so that an optical method involving triangulation with theodolites appears to be the only feasible procedure at this time. This necessarily restricts the observations to clear days. Fortunately this is not at present a serious limitation to us in the measurement of solar radiation, and we have therefore developed theodolites and a plotting instrument to permit such triangulation with great rapidity, and over distances somewhat greater than have been considered practicable for balloon-observation.

Balloon-visibility--The visibility of ordinary pilot-balloons at moderate altitudes has received considerable attention,because of its importance in routine observation of winds aloft. At an altitude of say 5.5 km, with half the weight of the atmosphere beneath it, a balloon may be observed either as a light object, or as a dark object against the brighter background of the sky. In general, the former is preferable, but even a small black pilot-balloon can be observed at this altitude if it is not more than 10 or 15 km distant. As the altitude of the balloon increases a larger and larger fraction of the sky-brightness is due to light-scatter between the observer and the balloon, and by the time an altitude of 15 km is reached the visibility-problem has changed materially. The sky above the balloon is relatively dark, and the balloon is to all intents and purposes being viewed against a black background, but through a light-scattering atmosphere illuminated by the Sun. Evidently then it must be viewed as a luminous object, not as a dark object against a lighter background. In other words, the balloon must reflect diffusely a substantial portion of the sunlight incident upon it.

Rubber balloons (which appear at present the only practical form) become very transparent when well distended, the ordinary type just prior to burst approaching almost the transparency of clear cellophane. For visual following this condition must necessarily be changed as the balloon will remain visible only if it continues to scatter sunlight. At our suggestion the Dewey and Almy Chemical Company of Cambridge, Massachusetts, has very kindly furnished us with balloons in which light-scattering white material has been incorporated in the latex. The improvement in visibility is marked, especially as the balloon approaches bursting diameter.

If the distance between a balloon and the observer is increased, with the former at constant altitude above the Earth, the visibility will decrease both because of the smaller angle subtended by the balloon and because of the increased mass of air between it and the observer, light-scatter in this air decreasing the contrast between balloon and surrounding sky. The former condition can be remedied by increased power of telescope. It is commonly supposed that this will in no way offset the effect of increased air-mass. However, a brief consideration will show that here too an increase in power of telescope is of advantage if the aperture of the telescope objective is increased in proportion to the magnification, so that the exit pupil remains unchanged, and providing that the astronomical "seeing" (freedom from refractive-index disturbances in the air near the telescope) is sufficiently good to permit using the higher power. The ability of the visual mechanism to detect a difference in brightness (the Weber-Fechner fraction) increases markedly with visual angle for pattern-details not far from the resolving power-limits of the eye. Since increase of magnification with constant exit-pupil diameter serves to increase the visual angle of a balloon without change in contrast or loss of field-brightness, a substantial gain in visibility may be expected from the use of larger telescopes than are ordinarily provided on balloon-theodolites.

From wind-roses up to four km published by Stevens [see 1 of references at end of paper) and from our own measurements at higher altitudes, we may expect on clear days in upper New York State a mean wind-velocity from the Earth's surface to the tropopause of perhaps 20 meters per second. For a balloon ascension-velocity of 5 meters per second, which is fast for instrument-carrying, this will place the balloon 14° above the horizon when entering the stratosphere, as

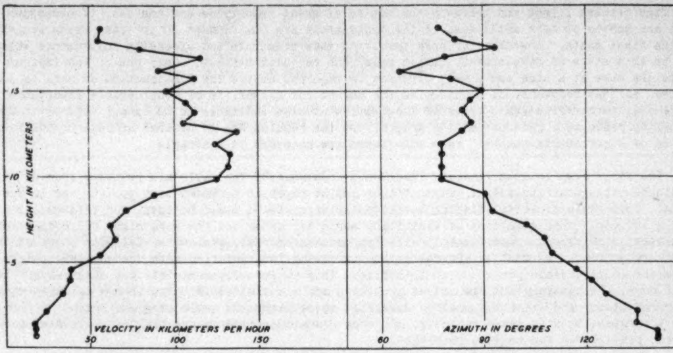


FIG. 1—TYPICAL WIND-DIAGRAM OVER ROCHESTER, NEW YORK, CLEAR DAYS IN MARCH AND APRIL

viewed from the point of release. Our experience indicates that the wind-velocity seldom drops abruptly above the tropopause, more frequently remaining nearly constant at over 100 km per hour until an altitude of 16 or 17 km is reached, at which level the velocity falls off. This will place the balloon about 12°.5 above the horizon when at 17-km altitude, the air in the line of sight under these conditions being more than four zenith-atmospheres. Above 16 or 17 km the angle of elevation of balloon above horizon will usually increase, the air-mass decreasing, and conditions for observation will become more favorable in spite of the increasing distance between observer and balloon.

We have thus far made double-theodolite observations on only a few flights to altitudes above 17 km, but of these the wind-diagram shown in Figure 1 appears to be characteristic for conditions over Rochester, New York, on clear days in March and April.

A light-scattering balloon two meters in diameter at 17-km altitude and 12°.5 above the horizon thus represents the most difficult part of a characteristic flight. The line-of-sight distance will be about 80 km and the balloon will subtend an angle of about 5". To provide a factor of safety, a condition of 4" subtended angle with balloon 10° above the horizon at a distance of 100 km and line-of-sight air-mass of 10 zenith-atmospheres has been assumed (doubling the actual air-mass to take care of slight haze), and our theodolites have been designed accordingly.

Theodolites--We have used as basic instruments Buff and Buff type ML-47 balloon-theodolites without telescopes or eyepiece tubes, having found from preliminary experiments that these instruments were sufficiently sturdy to carry large telescopes. The slow motions were altered slightly and the worms and gears completely enclosed to permit packing in grease, since smoothness of operation and freedom from back-lash is vital at high magnification.

Optical parts for the telescopes, computed by L. V. Foster to meet our specifications, were supplied by the Bausch and Lomb Optical Company. The objectives have a clear aperture of 80 mm, and a special design of pre-focusing eyepiece mount permits change of magnification during flight by several steps from 33 power to 83 power. The definition is excellent even at the highest power. By a telephoto combination this magnification is secured without the use of an eyepiece of unduly short focus, so that the eye-point can be maintained with comfort over long periods of observation. Telescopes and eyepiece tubes are constructed of high-strength duralumlnum and are completely counterbalanced. Photographs of these theodolites are shown in Figures 2 and 3. A detailed description of our instruments will be published in another place.

Plotting-instrument--To permit the plotting of balloon-position during flight, a rapid mechanical solution is required of the oblique ground-triangle formed by the base-line and the projection of the balloon upon the Earth's surface. Plotting-instruments for this class of problem are in common use for artillery-fire control, but no description of any suitable for our particular need seems to have been published. We have therefore designed a plotting-instrument which is shown in Figures 4, 5, and 6.

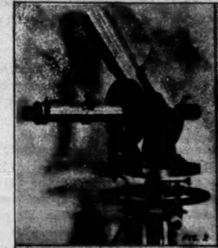


FIG. 2

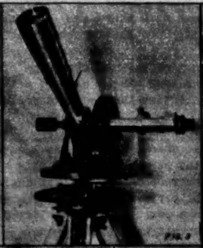
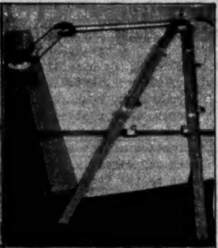
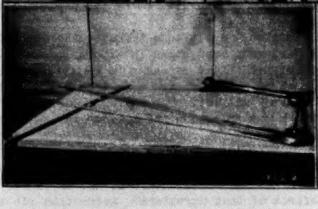


FIG. 3





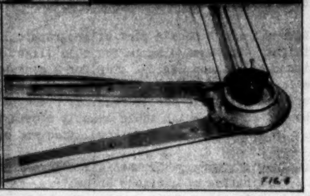


FIG. 6

The operation of this instrument will be evident from Figure 5. A commercial drafting-machine provides a protractor-head and parallel-motion to permit moving this head without change of orientation anywhere on the surface of a 42-inch by 60-inch drawing-board. To this have been added two independently adjustable arms which are carried on the protractor-head and are provided with verniers corresponding to the horizontal-circle verniers of the two theodolites. These arms, of duraluminum with a section designed for stiffness without undue weight, have their inner edges straight but offset from a radius through the protractor-center by an amount equal to the radius of the small cylindrical station-markers of diameter 0.500 inch, each of which is provided with a transparent bottom carrying center lines. These station-markers are carried on a steel strip independent of the plotting-instrument and are clamped to the board directly over the two ends of the base-line as located on the map.

We are using at present the maps of the United States Geological Survey on a scale of 1/62,500 or approximately one mile to the inch. By locating the base-line near one corner of the board we have been able to include most balloon-flights within the limits of the 42-inch by 60-inch surface. To take care of an occasional longer flight, provision is made for changing to half-scale at any time during a flight without losing the continuity of the settings.

The anchor-point of the parallel-motion is clamped to the plotting-board in the same manner as are commercial drafting-machines. The remainder of the instrument rolls on ball-bearings with suitable retaining rings, the surface of the plotting-board being maintained approximately horizontal.

Procedure--In use, the horizontal circles of the theodolites at the two ends of the base-line, which we may designate as stations A and B, are oriented alike either with zero on geographical north or on the direction of the base-line. The divided circle on the protractor-head of the plotting-instrument is set and clamped to coincide with the theodolite-circle orientation referred to the map, and need not be disturbed throughout the flight. Simultaneous readings of the horizontal and vertical circles of each theodolite, synchronized by radio signals or by accurate timepieces, are transmitted to the plotting-board. The two arms of the plotting-instrument are set to agree with the azimuth of the balloon respectively from A and B stations, and the instrument is moved on its parallel-motion until its two arms are in contact with the fixed cylindrical station-markers. This places the center of the protractor-head over the balloon's position as located on the map.

The protractor-head shown in Figure 6 is provided with a small permanently-centered pencil-compass, which is normally supported clear of the board by a spring. When the plotting-instrument is moved into position against the station-markers, pressure on the center post of this compass with the forefinger pricks a point on the map corresponding to the balloon's position, while spinning the knurled head beneath with thumb and forefinger draws a circle four mm in diameter to render the position-mark easily visible.

We have found the overall accuracy of this plotting-instrument equal to circle-settings of one minute of arc, yet a balloon's position can be plotted with great rapidity, in no case more than 30 seconds being required from the time the two theodolite-readings are received until the balloon's position is plotted.

Determination of the balloon's altitude requires the length of one leg of the ground-triangle which is read off directly on a special steel tape. A single slide-rule operation multiplying this distance by the tangent of the corresponding vertical angle gives the height of the balloon. This complete set of operations can be performed by one experienced man in less than one minute, so that, where necessary, the balloon's position may be plotted every minute. However, we have found observations at two-minute intervals more than adequate. When so spaced the operator at the plotting-instrument has time to construct in addition a wind-diagram as the balloon flies.

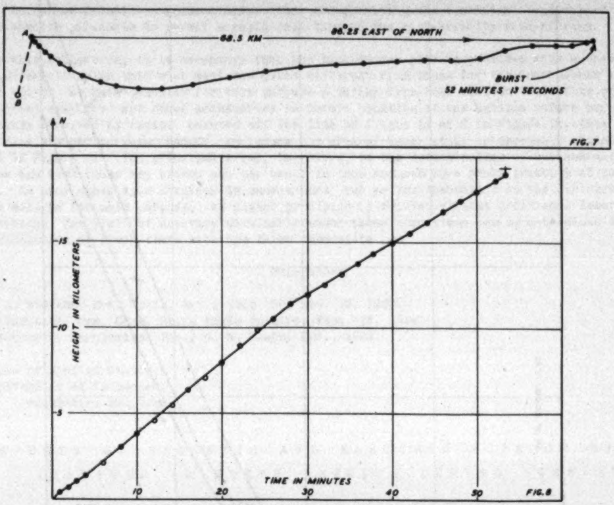
Figures 7 and 8 show a plot of geographical position and altitude throughout a characteristic flight. The wind-diagram for this flight has already been shown in Figure 1. The plot of altitude of balloon against time for a somewhat higher flight is shown in Figure 9. The observers for this flight were inexperienced and the three points marked with arrows are undoubtedly errors of horizontal-circle reading, since it is very unlikely that any vertical air-currents would be encountered which would exactly compensate so as to return the balloon to its original course. In the latter case, triangulation was continued on the falling fragments after burst.

Attainable accuracy--If the full accuracy of the method is to be realized, it is necessary, in the determination of altitude of balloon, to take account of curvature of the Earth and of atmospheric refraction which partly offsets the effect of that curvature. Refraction for a balloon within the atmosphere has been calculated in some detail by Poncelet [2]. We have combined his values for refraction with the correction for curvature of the Earth in a form convenient for rapid calculation. This is shown by the curves of Figure 10. It will be noted that the correction is always of the same sign, the actual altitude of balloon being always greater than that calculated without the correction.

The errors in double-theodolite observation have been discussed analytically by Poncelet [2], but when considered in combination with mechanical plotting it is more convenient to discuss these graphically. In Figure 11, A and B are two theodolites situated at the ends of the base-line and sighting on the point P. If the error in azimuth-determination lies within the limits shown by the dotted lines drawn from points A and B, the area of uncertainty within which P will lie is that shown by the heavy lines.

It is of interest to consider the magnitude of this area in a practical case. Consider a balloon at a distance of 100 km in a position approximately perpendicular to a 10-km base-line joining instruments A and B. Suppose that the azimuth-reading of either instrument may deviate one minute of arc on either side of the true azimuth, or a total spread of two minutes in the uncertainty of an azimuth-reading. In this case the area of uncertainty will be very nearly a rhombus with minor axis 60 meters and major axis 1200 meters long. The uncertainty in the measurement of distance from balloon to observer will thus be about 1.2 per cent, and this same uncertainty will be carried into the altitude-determination, being the principal source of error in this quantity. This is the condition likely to be encountered near the end of a long flight, and about the accuracy to be expected in triangulating upon a moving object with field-instruments. The base-line can be increased somewhat above 10 km, but this will be offset by the fact that the balloon will seldom lie in a direction perpendicular to it.

It will be evident that if the azimuth of balloon makes only a small angle with the base-line, the ground-triangle becomes quite inaccurate as has been pointed out many times,[3] and [2]. The vertical angles together with the azimuths permit a spherical-triangle solution which is fairly accurate if the vertical angles are sufficiently large. This does not lend itself as readily to mechanical plotting, however, and in any case is of an accuracy inferior to that attainable when the balloon-flight is roughly perpendicular to the base-line. A choice of two base-lines provided by a single station A and two alternate positions for the station B is thus very desirable. It is then only necessary to release a high-altitude pilot-balloon, preferably calibrated for ascension-velocity, from the base at A as soon as an instrument-carrying sounding-balloon flight is determined upon, the pilot-balloon being followed by a single theodolite at A. The general direction of drift is thus determined in time for the B-station party to occupy the preferred position. Since this pilot-balloon, if calibrated, also determines an approximate wind-



FIGS. 7 AND 8—GEOGRAPHIC POSITION AND ALTITUDE THROUGHOUT A CHARACTERISTIC FLIGHT

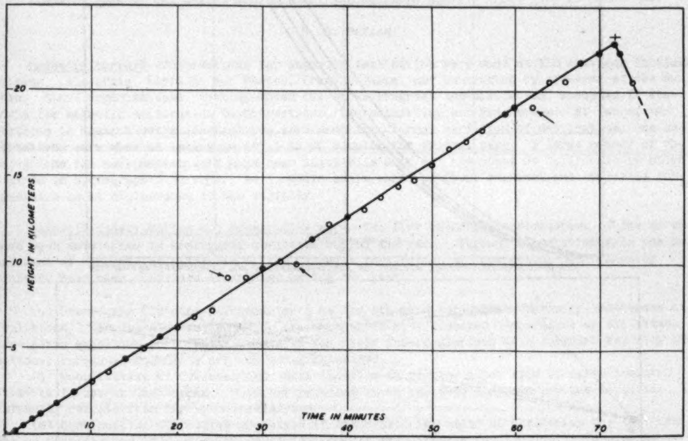


FIG. 9—PLOT OF PILOT-BALLOON ALTITUDE AGAINST TIME

diagram, the pick-up car may leave the base when the pilot-balloon is released, and, following radio advices, travel in the direction of drift for some time before the release of the instrument-bearing sounding-balloon. Since a car cannot in general keep pace with a drifting balloon, the preliminary pilot-flight is necessary for this reason alone. A choice in the base-line position is thus secured without additional balloons or delay.

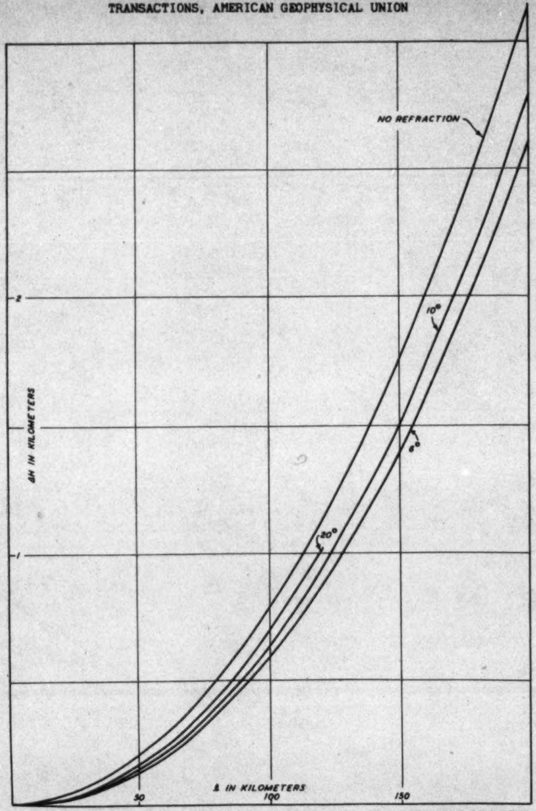


FIG. 10—CORRECTION-GRAPHS ACCOUNT OF EARTH-CURVATURE AND ATMOSPHERIC REFRACTION

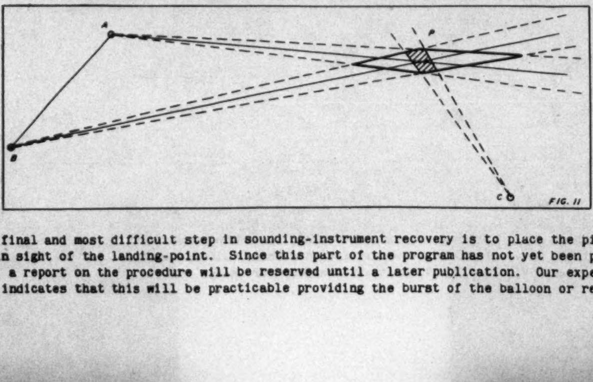


FIG. 11

The final and most difficult step in sounding-instrument recovery is to place the pick-up car within sight of the landing-point. Since this part of the program has not yet been put into practice, a report on the procedure will be reserved until a later publication. Our experience thus far indicates that this will be practicable providing the burst of the balloon or release of the instrument from it is mechanically timed, and providing the instrument is equipped with a delayed-opening parachute to permit a rapid fall through the high-velocity wind-streams.

In this connection, it is necessary that the pick-up car also be provided with a theodolite. The requirements which this must meet are quite different from those for the instruments at stations A and B. We have selected for this purpose a Gurley-type 4520 balloon-theodolite provided with special eyepieces and other accessories to permit location of the balloon before burst from coordinates received by radio. Located off the line of flight as at C in Figure 11, this theodolite serves another purpose, namely, to reduce the area of uncertainty to the small shaded region about P in Figure 11. The principal error, therefore, in the determination of balloon-altitude, which as has been shown may exceed one per cent, is thus reduced to a small fraction of this amount. In many cases such accuracy is unnecessary, but as the theodolite on the car serves this as well as its main purpose, the higher precision is secured without additional labor or complication. The limit of accuracy attainable under these conditions can be determined only after completion of field-tests with the third theodolite.

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REPORTS ON MAGNETIC AND ELECTRIC WORK OF ORGANIZATIONS IN NORTH AMERICA DURING 1936-37

MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY, APRIL 1936 TO MARCH 1937

R. S. Patton

Magnetic surveys--Observations for magnetic declination were made at 113 stations in Alaska, Arizona, California, Florida, New Mexico, Oregon, Texas, and Washington by officers of the Bureau. State organizations, working under the Works Progress Administration, occupied 72 stations for magnetic declination in Connecticut, Massachusetts, and New Jersey. At two of the stations in Massachusetts observations were made for diurnal variation of declination; the observations were made at intervals of 15 to 20 minutes for several days. A large number of observations for declination were made near Sixty-Mile-Bank off the coast of California by ships engaged in hydrographic surveys. An isogonic chart based on these observations indicates considerable local disturbance in the vicinity.

Magnetic observatories and cooperative work--The five magnetic observatories of the Bureau have been maintained in continuous operation during the year. Through cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the following projects have been continued or started during the year:

(a) Use of the CIW sine-galvanometer 1 as the standard horizontal-intensity instrument at Cheltenham. The standard cells, which are maintained at a constant temperature at all times, have given excellent performance. Details for their intercomparison with standard cells by the National Bureau of Standards are now being developed.

(b) Substitution of CIW standard earth-inductor 48 for the older type of earth-inductor formerly in use at Cheltenham. This has resulted in an improved standard for the vertical-intensity results from Survey observatories.

(c) Continuation of routine operation of the cosmic-ray meter at Cheltenham for the Committee on Coordination of Cosmic-Ray Investigations of the Carnegie Institution of Washington.

(d) Continuation of standardization of all magnetic instruments of the Carnegie Institution of Washington and of the Survey at Cheltenham Observatory--in cooperation with the staff of the Institution's Department of Terrestrial Magnetism.

(e) Continuation of operation of the CIW perminvar vertical-intensity variometer at Cheltenham on an experimental basis with the cooperation of A. G. McNish of the Institution's Department of Terrestrial Magnetism.

(f) Continuation of atmospheric-electric and earth-current programs at the Tucson Magnetic Observatory.

Through cooperation with Science Service, magnetic character-figures for all American observatories are broadcast weekly from Station W1XAL of the Wide World Broadcasting Foundation of Boston, Massachusetts. The magnetic condition of the day as determined every morning from the magnetograms recorded at Cheltenham Observatory is broadcast daily from the same station.

The Danish Meteorological Institute of Copenhagen, Denmark, has loaned to the Bureau for a period of six months a quartz horizontal magnetometer for use in making intercomparisons of horizontal intensity at widely separated observatories. The instrument, devised by Dr. D. la Cour of the above Institute, is now being compared at Cheltenham and preliminary results indicate that it may be quite useful in maintaining observatory-standards.

The Louisiana State University is constructing a temporary magnetic observatory for absolute observations at Baton Route, Louisiana, and with instruments loaned by this Bureau it is expected that an extended program of diurnal-variation observations of declination and horizontal intensity will be carried on by that University. The results will be made available for use and for publication by the Survey.

Special investigations--(a) Special investigations of orientation of variometers have been continued in the Washington Office and at Cheltenham Observatory. (b) Extended comparisons of a Toepfer variometer and a la Cour vertical-intensity variometer have shown that, after application of second-order temperature-corrections, the difference of the base-line values for the two instruments is practically constant for extended periods. Apparent irregularities of the base-line values are therefore ascribed to persistent errors of the absolute observations. (c) Special tests at the Cheltenham Observatory indicate that earth-inductor 26 has a temperature-coefficient which is quite appreciable.

Publications--(a) Good progress has been made in preparation of results at the magnetic observatories for publication. (b) "Magnetic declination in the United States for 1935" was received from the printer in March 1937 and is being distributed. (c) Results at the Tucson Observatory in 1927 and 1928 have been distributed.

Miscellaneous--(a) Magnetic character-numbers for the observatories operated by the Bureau from 1900 to 1905 were furnished to the International Commission of Terrestrial Magnetism and Atmospheric Electricity. Steps have been taken to determine character-numbers for observatories operated between 1880 and 1900. (b) This Bureau has been operating a geodetic computing office in New York with funds allotted by the Works Progress Administration and, since February 1, 1937, a considerable amount of magnetic computing work has been done at that office.

U. S. Coast and Geodetic Survey,
Washington, D. C.

IONOSPHERE-RESEARCHES OF THE NATIONAL BUREAU OF STANDARDS

J. H. Dellinger

The program of regular measurements of ionospheric layer-heights and ionization has been continued along the same lines as reported in previous years. Progress was made in correlating the data with the facts of radio transmission at different frequencies and times. This was facilitated by continuous recording of field-intensities from several radio stations.

Summaries of the monthly averages, for each hour of the day, of virtual heights and critical frequencies for E-, F_1-, and F_2-layers were prepared and sent to interested laboratories monthly. As in past years, data were sent to Science Service for the Ursigrams each week.

An outstanding result is the determination of a striking increase of ionization of all the ionospheric layers, keeping pace with the increase of sunspots. This has been in evidence since 1933, the last sunspot-minimum. In 1936 the ionization reached values exceeding any previously measured.

A study of ionospheric changes during magnetic storms indicated marked effects especially in the F_2-layer. The principal effects observed were as follows: (1) Disturbed radio conditions correlate much better with disturbances of the Z- than with the H-component of the Earth's magnetic field; (2) a severe magnetic disturbance beginning during the daytime may show little correlation with radio data for that day, while a severe magnetic disturbance before sunrise is followed by disturbed radio conditions during the whole of the following day; (3) the disturbed radio conditions include lowered critical-frequencies, increased absorption, and increased virtual-heights indicating a diffusion of the ionosphere; (4) during a magnetic disturbance the higher part of the ionosphere is the most disturbed.

By means of the Bureau's ionosphere and field-intensity records, supplemented by reports from many observers in various parts of the world, an exhaustive study was made of sudden ionospheric disturbances. These sudden effects produce a cessation of long-distance high-frequency radio transmission and in many cases simultaneous perturbations of terrestrial magnetism and atmospheric electricity. They are most intense where the Sun's radiation is perpendicular, that is, at noon and in low latitudes, and do not occur in the dark hemisphere. Many of them have occurred simultaneously with visible solar eruptions. They appear to be due to sudden increase of ionization in a region below the E-layer, caused by emission of certain radiation from solar eruptions.

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National Bureau of Standards,
Washington, D. C.

REPORT ON RESEARCH IN TERRESTRIAL MAGNETISM BY THE DEPARTMENT OF GEOLOGY OF THE UNIVERSITY OF NORTH CAROLINA

W. F. Prouty

At the present time, the Department of Geology of the University of North Carolina is carrying on investigations in the folded Appalachians, in the Piedmont Plateau, and in the Coastal Plain Area. One of the most interesting lines of investigation is trying to determine the origin of the numerous elliptical bays and lake-basins in North and South Carolina. The magnetometer has demonstrated the presence of a magnetic high in association with practically all the medium to large-size elliptical bays and lake-basins in all parts of the Coastal Plain. The highs are better developed in the portions away from the Coast. Insufficient work has, however, been done in the areas between the bays to make certain of the freedom of such areas from "spot"-highs of the type associated with the bays. Funds are now being sought to carry on this detailed "grid"-survey.

Magnetometer cross-sections of the Coastal Plain of South Carolina and North Carolina have already brought out some most interesting facts. The buried Triassic trough near Florence, South Carolina, has been found to be about 14 miles wide near Florence. This basin has been traced some distance to the southwest and well into North Carolina, in a northeastwardly direction. It is thought that the surveys have demonstrated a steeper slope to the crystalline-rock floor of the Coastal Plain near the ocean. It is thought also that other troughs or erosional valleys exist in the buried crystalline-rock floor. Well-defined linear highs also suggest that it may be possible to work out some larger structures in the crystalline-rock floor, as well as to get some idea as to depth- and slope-conditions. These problems must also await financial aid before they can be successfully carried on.

Much work has already been done in getting boundaries of the Durham Triassic Basin and also in mapping structures, igneous sills and dikes, and in getting depth-readings. In this work both magnetometer and electrical resistivity-methods have been employed.

At the present time, also, magnetometer-surveys are being made in the folded Appalachian Area of southwestern Virginia. This survey is made with the idea in mind of checking known structures with observed magnetometer-readings.

University of North Carolina,
Chapel Hill, North Carolina

REPORT ON STRATOSPHERE RESEARCH AT THE UNIVERSITY OF ROCHESTER

Brian O'Brien

With aid from the Smithsonian Institution, we have undertaken a preliminary study of fluctuations in the ultra-violet output from the Sun. In order to free these measurements as far as possible from uncertainties in atmospheric transmission it has seemed desirable to attempt them from high-altitude sounding-balloons working well into the stratosphere. At present we are using filters to isolate a wave-length region slightly longer than the Hartley band of ozone, so that there are no uncertainties in atmospheric transmissions due to fluctuation either in the amount or vertical distribution of the ozone.

In connection with this program we have completed a subsidiary development which is of interest in upper-air exploration with sounding-balloons. The development involves a procedure and instruments for the continuous triangulation upon a balloon while in flight, and the transmission of the balloon's position to a pick-up car, or cars, in the field, in order to expedite the recovery of valuable apparatus. The development is not completed in all respects, but that part pertaining to the continuous triangulation and plotting during the balloon's flight is complete, and has been through successful field-tests. In principle it is, of course, very simple. In detail, however, it has required the development of two unusual balloon-theodolites of great telescopic power, and a mechanical plotting-instrument of accuracy comparable to the theodolites to permit minute-to-minute determination of the coordinates of the balloon in space. The scheme has proved workable, even with very small sounding-balloons, up to distances of 100 km or more and provides a powerful tool for this class of work.

University of Rochester,
Rochester, New York

REPORT ON AURORAL RESEARCH AT THE UNIVERSITY OF ALASKA

E. H. Bramhall

As Miscellaneous Publication No. III of the University of Alaska, a report on the results of auroral measurements and observations at the University of Alaska during the years 1930-1934 is now in the hands of the publisher.

This research, made possible through the generosity of the Rockefeller Foundation, has been partially covered in several articles published in the Journal of Terrestrial Magnetism and Atmospheric Electricity (December, 1931; June, 1932; September, 1933; September, 1935) by the late Professor Veryl R. Fuller. The present report includes the material published in these papers and extends the calculations made from simultaneous parallactic photographs obtained by Professor Fuller and his collaborators through December, 1934, at which time the five-year program, for which the grant was made, was completed.

University of Alaska,
College, Alaska

MAGNETIC WORK OF THE DOMINION OBSERVATORY, OTTAWA, DURING 1936

R. Meldrum Stewart

In the process of a reorganization affecting certain branches of the Canadian Government service, a transfer was made on December 1, 1936, of the work and personnel of the Magnetic Division of the Meteorological Service to the Dominion Observatory, Ottawa. The work of the magnetic observatories and that relating to the magnetic survey of Canada will in future be under the direction of the Dominion Astronomer.

Magnetic observatories--Canada has at present two permanent magnetic observatories. One situated at Agincourt, near Toronto, has been in continuous operation since September, 1898, when it replaced the one at Toronto which had commenced operations in 1839; the other is situated at Meanook, about 90 miles north of Edmonton, Alberta, where it has been in continuous operation since 1916.

At Agincourt the equipment now consists of one set of Kew-type photographic recording-variometers, the elements recorded being D, H, and Z with sensitivities of 1'.28, 4.86γ, and 7.79γ, respectively, one set of la Cour variometers also recording D, H, and Z with sensitivities of 0'.928, 5.24γ, and 5.90γ, respectively, and one set of la Cour quick-run variometers. The absolute observations for D are made with Elliott magnetometer No. 48, for H with Schuster-Smith coil-magnetometer, and for I with Toepfer earth-inductor No. 98.

At Meanook the equipment consists of one set of la Cour variometers recording D, H, and Z with sensitivities of 0'.956, 8.06γ, and 10.74γ, respectively, and one set of la Cour variometers recording D, H, and Z with sensitivities of 2'.3, 22.2γ, and 16.7γ, respectively. There is also one set of Kew-type variometer for D, H, and Z, of which only the H is at present in operation at sensitivity of 9.22γ per mm. Absolute observations at Meanook are made with Elliott magnetometer No. 98 for D and H and with earth-inductor made by the Meteorological Service for I.

Magnetic survey--During the year, observations of the three magnetic elements, declination, inclination, and horizontal intensity, were made at 16 stations. Thirteen of these are repeat-stations, results from which will furnish important secular-change data, and three are new. The work was confined to the southeastern part of Canada between latitudes 44° 38' north and 50° 08' north, and longitudes 59° 58' west and 97° 07' west. In addition to the field-work, the usual instrumental comparisons were made at the end of the observing season. The magnetic instruments now used by the British Canadian Arctic Expedition under the leadership of T. H. Manning were standardized and instructions in methods of observing were given to members of the party.

Dominion Observatory,
Department of Mines and Resources,
Ottawa, Canada

REPORT ON COSMIC TERRESTRIAL STUDIES

Harlan T. Stetson

The measurements of the field-intensities of radio station WBBM, Chicago, have been continued in the Boston Area. With the departure of Dr. G. W. Kenrick for Puerto Rico, and the subsequent interruption of the series carried on by him at Tufts College, Medford, Massachusetts, the recorder was set up again in Cambridge--temporarily at the Institute of Geographical Exploration in the spring of 1935. The apparatus was removed to Waban, Massachusetts, November 1, 1935, as the receiving conditions in this suburb avoided certain local interferences that had proved troublesome.

Records have been maintained continuously in Waban from that date. The apparatus was modified to the extent of introducing an automatic time-switch that would connect and disconnect both the recorder and the receiver at appropriate hours for covering a whole night's program. Field-intensities have grown in general constantly lower with the present rise in sunspot-numbers. During the extraordinary activity of the Sun in late January and early February, 1937, field-strengths were so low as to be below the threshold-value of the recorder, but recovery came in ten days after this peak in maximum solar activity. Records are being reduced, and will be given more complete discussion at a later date.

With the idea that changes in electron-density in the ionosphere may be accompanied by possible changes in the distribution of ions in the lower atmosphere, measurements have been systematically made with an ion-counter (similar to the Everett type) at the Massachusetts Institute of Technology. Thus far, readings during daylight have been made hourly from $9^h 00^m$ to $17^h 00^m$. These records show a systematic rise to a peak shortly after noon, with a corresponding fall in the afternoon. The seasonal variation also appears. It is hoped that the apparatus may soon be made automatically recording so that counts of both negative and positive of known mobility may be had continually for all hours of the day and night to supplement similar work being done in other localities.

Further investigations are in progress relative to the lunar effect in radio transmission already reported. Some confirmations have come in from other observing stations. It is believed that continued measures of radio field-intensities and also counts of large and small ions may furnish important data contributory to the field of cosmic and terrestrial relationships, in which the electronic content of the atmosphere appears to play an important part.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

REPORT OF THE SECRETARY TO THE EIGHTEENTH ANNUAL MEETING OF THE SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

E. O. Hulburt, Secretary

There were no special meetings of the Section during the year. The minutes of the Seventeenth Annual Meeting were sent to all members. No corrections or additions were received.

The Edinburgh meeting of the International Association of Terrestrial Magnetism and Electricity was noteworthy because of its distinctly international aspect. Sixty-five delegates and guests represented 17 countries at the eight meetings of the Association. There were 20 reports for national committees and over 60 communications, the majority of which concerned researches requiring international coordination and cooperation. The Hydrographer of the British Admiralty announced that the plans of the non-magnetic vessel Research to resume the magnetic and electric surveys of the oceans originally carried on by the Carnegie had been completed and that in this effective assistance had been received from W. J. Peters of the Carnegie Institution of Washington, as also in the design and plans for necessary instruments. He further advised that the contract for the construction of the vessel had been let. Mr. Peters returned from England in September, 1936, after having been consultant there for a year in this work.

Nineteen resolutions pertaining to international research and cooperation in the fields of the Association were adopted. The Department of Terrestrial Magnetism of the Carnegie Institution of Washington was delegated to prepare and publish a list of magnetic and electric observatories and thesaurus of values. Emphasis was placed on the necessity of control of variometers and of examination at regular intervals in the operation of observatories, on the desirability of installing at all observatories insensitivie magnetographs so that no details of severe magnetic storms would be lost. Steps to further promote international comparison of magnetic standards were taken. In the future publication of numerical magnetic-activity figures according to the agreement at Stockholm in 1930, it was agreed to replace ($HR_H + ZR_Z$) by the daily range of declination expressed in minutes of arc. Arrangements were made for the extension of magnetic character-numbers on the scale of 0, 1, and 2, to observatory-results obtained prior to 1906.

The desirability of continuing and extending atmospheric-electric programs at observatories was emphasized, as also the provision of more earth-current stations at well-distributed points.

New committees were established on magnetic charts, on giant pulsations in Iceland, on methods of observatory-publication, on classification of magnetic literature, on comparisons of international magnetic standards. A new committee of particular interest to us in the United States is the joint committee of the International Scientific Radio Union and the Association with Appleton as Chairman and Berkner as Secretary. Membership of the various committees includes many Americans. New officers for the next three years were elected as follows: President, J. A. Fleming; Vice-Presidents, Ch. Maurain and S. Chapman; Secretary and Director of Central Bureau, A. H. R. Goldie; additional members of the Executive Committee, Keränen and Tanakadate through 1939, van Dijk, Crichton Mitchell, and Störmer through 1942.

Besides the progress made at the Edinburgh Assembly of the International Association, an advance was made in an investigation of the recorded magnetic and radio conditions observed on several occasions during the past year at the times of bright outbursts of light in the regions of sunspots. Besides radio fade-outs simultaneous with these disturbances, sudden changes in the Earth's magnetism occurred. This definite relation between solar disturbances and terrestrial disturbances in the Earth's magnetism and in radio communication promises much in the investigation of the physical reasons underlying these phenomena.

Another development during the year was the initiation early in March of a weekly compilation of magnetic character-numbers as determined from seven American-operated observatories for the Greenwich half-days of the preceding week. These character-figures are based on a scale of 0, 0.5, 1.0, 1.5, and 2.0. An examination of previous records has shown the averages for these observatories to be generally in good agreement with international character-figures which are available only after six to eight months. The fact that character-figures resulting from these seven observatories [five of the United States Coast and Geodetic Survey and the Huancayo (Peru) and Watheroo (Western Australia) observatories of the Carnegie Institution of Washington] are being thus made available so quickly after compilation by the Department of Terrestrial Magnetism through Science Service will make available for prompt study of correlations practically world-wide character-figures.

It is of interest to record the establishment of a new observatory, the San Miguel Cosmophysical Observatory, Buenos Aires, Argentina.

Preliminary notices of the Eighteenth Annual Meeting were sent to all members from the office of the General Secretary on February 27, 1937. In compliance with the objects of the Union as stated in the Statutes and By-Laws, namely, to promote and coordinate the study of various branches of geodesy and geophysics in American and outlying territories, brief summaries of work carried on by the various organizations and individual investigators during the year have been collected for incorporation in the Transactions of the Eighteenth Annual Meeting. These may be listed briefly as follows:

Dominion Observatory, Canada--Magnetic survey of Canada and Territories for secular variation; standardization of instruments for the British Canadian Arctic Expedition.
National Astronomical Observatory, Mexico--Magnetic survey.
Stanford University--Atmospheric electricity; electron-mobilities.
Colorado School of Mines--Magnetic survey; earth-resistivity.
Mount Wilson Observatory, Carnegie Institution of Washington--Terrestrial-magnetic activity; sunspots and solar spectroheliograms in hydrogen light.
University of Alaska--Auroral investigations.
University of California at Los Angeles--Laboratory auroral and night-sky spectra.
University of North Carolina--Magnetic survey of the Coastal Plain.
University of Rochester--Ozone, solar ultra-violet light.
Department of Terrestrial Magnetism, Carnegie Institution of Washington--Geomagnetic charts; reduction and study of accumulated magnetic data; continuous records at the Huancayo and Watheroo magnetic observatories; ionospheric investigations in Peru and Australia; electricity of the lower atmosphere; nuclear investigations with high voltage; cosmic rays.
National Bureau of Standards--Investigations of ionosphere; field-intensities of high-frequency radio; radio fade-outs; dissemination of ionospheric data for daily radio broadcast of cosmic data under the auspices of Science Service.
United States Naval Research Laboratory--Ionosphere; direction of static.
United States Coast and Geodetic Survey--Continuous records of five magnetic observatories; magnetic surveys; instrumental development.

The total membership of the Section is 199, an increase of 23 over last year.

U. S. Naval Research Laboratory,
Washington, D. C.

PROGRESS-REPORT ON RESEARCHES IN TERRESTRIAL MAGNETISM AND ELECTRICITY AT DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION OF WASHINGTON, FOR YEAR APRIL 1936 TO MARCH 1937

J. A. Fleming

Since the report published in the Transactions of the Seventeenth Annual Meeting, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington has continued activities along the same general lines, namely: (1) Maintenance of field-work for the purpose of secular-variation studies and of observatory-records of the continual changes in the Earth's magnetic and electric fields; (2) development of magnetic and electric apparatus for use in the field and at observatories; (3) development of apparatus for recording ionospheric conditions, thus permitting their investigation and correlation with other geophysical phenomena; (4) theoretical formulation and experimental investigation of the fundamental aspects of nuclear physics; (5) reduction and study of accumulated observational data.

Work in the field and at observatories

Since only limited funds could be apportioned for magnetic-survey work, the amount of field-work to be undertaken was restricted. The principal field-operations were conducted by W. C.

Parkinson who early in 1936 inaugurated an extensive program in Australasia and the Pacific Islands. Using Sydney, New South Wales, as a base, during June 1936 to April 1937, he completed five expeditions, namely: Queensland and New South Wales (11 stations); Victoria and Tasmania (6 stations); Solomon Islands, New Guinea, and Papua (15 stations); New Zealand (12 stations); Gilbert Islands, Ocean Island, and Nauru Island (6 stations). Data at stations in North Australia South Australia, and China were obtained also in cooperation with organizations in those countries through the loan of magnetic instruments.

The Department continued cooperation with the British Admiralty on the designs of the non-magnetic vessel Research and of the instrumental equipment. The assignment for one year of William J. Peters as consultant at London in these matters ended in September 1936. Tests and determinations of constants for CIW-type magnetometer-inductor No. 111, manufactured by the Precise Instrument Company of Brooklyn, New York, were made and the corrections on International Magnetic Standards of the Department were determined at Washington and at Cheltenham.

Tests have been made on the magnetic properties of core-samples (the majority 9 to 10 feet in length) obtained by the Geophysical Laboratory of the Carnegie Institution of Washington from the ocean-bottom. Some of these cores appear to be highly magnetic and this investigation may yield information about the Earth's field in early times; it may be possible also to interdate portions of various cores by similarities of their magnetization.

The use of the rotating coil of the earth-inductor to determine the direction of the Earth's magnetic field, and in particular to determine the inclination of the field, is one of the best means of obtaining through computation the vertical component of the Earth's magnetic field. A study of the application of alternating-current methods of detection to earth-inductors, for observations on sea and land, conducted at the Department shows that it is possible thus to determine inclination and declination at sea with considerably greater accuracy than by previous methods, while on land more accurate measurements may be made with rugged apparatus more quickly than heretofore. Using a continuously rotating coil, the earth-inductor may be used as a recording declinometer and inclinometer.

The observatories of the Department at Watheroo in Western Australia and at Huancayo in Peru continued photographic registrations of the magnetic, atmospheric-electric, earth-current, and ionospheric elements and associated meteorological and solar data. Cooperation was maintained in the atmospheric-electric work in progress at the Apia Observatory in Western Samoa and in the atmospheric-electric and earth-current work at the Tucson Observatory of the United States Coast and Geodetic Survey in Arizona. Cooperation was extended the United States Coast and Geodetic Survey in maintaining both Department and Survey standards at the Cheltenham Magnetic Observatory through the continued installation there of the CIW sine-galvanometer 1. The CIW induction-variometer was operated at that Observatory since last year's report. Its performance has been consistent and quite satisfactory.

The ionospheric records obtained at the Watheroo and Huancayo magnetic observatories have revealed numerous fade-outs and they permit a continuous investigation of the nature and cause of fade-outs. The great difference in longitude of these observatories makes possible an almost complete record of such phenomena because at any time either one or the other is in sunlight.

In cooperation with the United States Coast and Geodetic Survey, there was begun in March 1937 weekly compilation of magnetic character-numbers on a scale of 0, 0.5, 1, 1.5, and 2, for each Greenwich half-day. These are based on telegraphic weekly summaries from seven American-operated magnetic observatories, namely, Cheltenham, Tucson, Sitka, Honolulu, and San Juan of the United States Coast and Geodetic Survey, and Huancayo and Watheroo of the Carnegie Institution of Washington. The daily averages of these seven character-numbers are compiled at the Department of Terrestrial Magnetism each week and communicated to Science Service. That Service then distributes promptly mimeographed copies to communication-systems and interested parties. Examination of available figures for past years have shown these seven stations to yield mean character-numbers in generally good agreement with the international character-numbers. Thus investigators have available, for use in prompt study of correlations, world-wide character-numbers applying for the preceding week instead of having to wait for the international summary some five to six months later.

Instrumental developments

The automatic multifrequency recording instruments, after being subjected to thorough tests, have now been perfected and are being sent to the Huancayo and Watheroo observatories. A manual equipment was supplied the Central China College, Wuchang, China, where it will be operated under the supervision of Prof. C. T. Kwei. Certain anomalies in the F_2-region ionization may be explained through the strategic location of this station which, in the Northern Hemisphere, is in practically the same longitude as Watheroo.

In terrestrial electricity, new equipment for measuring the atmospheric-electric elements in the high atmosphere from aircraft was completed. Studies of the effect of inhomogeneity of the electrical conductivity of the Earth on the circulation of earth-currents were made. Measurements bearing on the so-called vertical earth-currents were obtained on Pass Mountain, Virginia. Although the diurnal variation in earth-currents could be detected, no general evidence of a vertical earth-current was found; there was, however, an apparent steady flow up one side of the Mountain and down the other.

Magnetic and electric investigations

Maps of the secular variation for the entire Earth were constructed for the period 1885-1922. They show that the secular change over extensive areas is comparable in magnitude with the field due to the harmonics above the first degree. Extensive compilations by least squares of the declination-values determined on the ten cruises of the Galilee and the Carnegie during 1905 to 1929 and of secular variation in the Pacific Ocean were nearly completed.

An investigation of the recorded magnetic conditions following three notable intense flares of ultra-violet light from the Sun observed during 1936 revealed that these flares were not followed by magnetic storms. The magnetic effects produced by these flares were found to be entirely different in character from those common to magnetic storms. It is concluded that the ultra-violet light theory of magnetic storms is not confirmed.

An intensive investigation made of the effect of bright chromospheric eruptions on radio communication and terrestrial magnetism showed that the more intense flares enhance ionization in low levels of the ionosphere. This enhancement produces increases in the electric currents responsible for the diurnal variation of terrestrial magnetism and causes absorption of high-frequency radio waves entering this region.

The field of magnetic storms which is independent of local time was studied by comparison of the vector-differences of the magnetic field on disturbed and quiet days at 19 widely distributed observatories during the magnetically active year 1927. The data, ordered according to the geomagnetic coordinate-system, were fitted by the first four zonal harmonics of odd degree. So closely did the directions of the vectors correspond to the geomagnetic directions that it was not deemed necessary to use harmonics involving longitude-terms. Coefficients determined separately from the horizontal and vertical components of intensity permitted separation of the field into those portions due to internal and external portions. The ratios of the coefficients of the several internal and external harmonics indicate that the internal portion is not a result of simple induction, but it is complicated by other factors--perhaps the non-homogeneous conductivity of the Earth due to oceanic areas or to a complicated mode of variation of the external harmonics, such as might arise because of a shifting of the auroral zone in storms of greater or lesser intensity.

Assuming that the magnetic effects were due to electric currents flowing in spherical shells concentric with the Earth, current-systems were constructed to represent the variations. The external current-system was found to have three regions of maximum density--one at the geomagnetic equator and the other two about 20° from each of the geomagnetic poles. Similar maxima were found for the internal system, the poleward maxima being closer to the geomagnetic equator.

In an investigation of the relation between condensation-nuclei and the various atmospheric-electric and meteorological elements as observed at the Huancayo Magnetic Observatory, the nuclei show a marked response to the variations in rainfall. There was a conspicuous diminution in the number of nuclei during the rainy seasons with accompanying variations in the atmospheric-electric elements. The conductivity is greater when numbers of nuclei are small, the potential gradient being higher at these times.

The value of the coefficient of combination between small ions and large ions was determined from data simultaneously obtained on small-ion and large-ion concentrations in the atmosphere and on the rate of small-ion formation. The average value for the coefficient was found to be about 9.0×10^{-6} with a considerable range in the values, the largest being more than twice the smallest. The combination-coefficient was found to vary with temperature and absolute humidity of the air, the correlation with both being between +0.5 and +0.7. One interpretation of the results is that the combination-coefficient varies because the size of the particle of which the large ion is composed varies with absolute humidity.

Studies at the Department of Terrestrial Magnetism have disclosed that small particles, numbering some 200,000,000, are expelled from the lungs in each breath. These tend to accumulate in the air of a closed room occupied by people and, to some extent, are taken into the lungs of other individuals in the room. A possible cause for the development of "bad" air is the accumulation of such small breath-particles and a method of eliminating this accumulation is desirable. Since further investigations show the majority of such particles to be charged, it should be possible to remove them with an electric filter, thus immediately revitalizing the air. The recognition of this should lead to important advances in the field of air-conditioning.

A statistical analysis was made of continuous cosmic-ray intensity data for some 360 complete days as recorded at the Cheltenham Magnetic Observatory of the United States Coast and Geodetic Survey. This is one of the world net of cosmic-ray recording stations established by the Carnegie Institution of Washington equipped with precision cosmic-ray meters after the design for the Institution by Compton, Wollan, and Bennett. The results show that the real barometric coefficient does not change from hour to hour or from month to month. The effect of external air-temperature upon the intensity, reported by some observers, was not found. The data have been subjected to modern statistical methods which provide an objective measure for the probability that the observed diurnal-variation is real. The results indicate, for the period covered by this analysis, a physically significant 24-hour wave in apparent cosmic-ray intensity, with an amplitude of 0.17 per cent of the total intensity, having its maximum at about 11^h, 75° west meridian mean time.

Results in nuclear physics

Measurements of the total absolute yield of neutrons from various reactions were made over the voltage-range between 300 and 1000 kilovolts using the technique developed by Amaldi and Fermi. These measurements make possible an immediate comparison of the intensity of artificial neutron-sources with that of the usual 500-millicurie (Rn + Be) sources used for the production of neutrons. For the (Be + D) reactions at 1000 kilovolts, for example, each microampere of target-current gives a neutron-yield equal to 6800 millicuries of (Rn + Be). Knowledge of the absolute yield also permits an immediate calculation of the actual amounts of the artificially radioactive material, measured in millicuries (or in grams) which can be produced by existing apparatus.

An investigation was carried out on the transmutation-processes of Li^6 and Li^7. Thin targets of the separated isotopes of these isotopes were used for the investigation of alpha-particle, proton, neutron, and beta-particle excitation-functions under deuteron-bombardment for voltages between 200 and 1000 kilovolts. Observations were made on the voltage-dependence of the separation and relative intensity of the components of the proton doublet from Li^6. The excitation-curves show markedly different characteristics, dependent both upon the disintegration-product and the parent nucleus.

Observations on the scattering of protons by protons were extended to the energy-region below 600 kilovolts by using a Geiger point-counter to detect the scattered and recoil protons. The angular variation of these protons was investigated at the fixed voltages 200, 300, and 400 kilovolts. The data clearly indicate a large decrease in the ratio of the observed scattering to Mott's theoretical scattering at 45° in the region of 300 to 400 kilovolts, as would be expected on the basis of the attractive forces demonstrated by our measurements a year ago. The absolute values of the scattering are not yet satisfactorily quantitative owing to the presence of residual counts probably caused by ultra-violet light.

Publications

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Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

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AMERICAN GEOPHYSICAL UNION

Eighteenth Annual Meeting

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THE OCEANOGRAPHIC WORK OF THE HYDROGRAPHIC OFFICE AND THE UNITED STATES NAVY FROM APRIL 1936 TO APRIL 1937

H. E. Kays

As in the past years, the oceanographic activities of the Hydrographic Office and the United States Navy were many and varied, extending over widely separated areas.

United States Naval surveys--The hydrographic chart of today is more than a portrayal of general ocean-topography and accurate delineation of coast-line. In addition to the hydrographic detail inside the 100-fathom curve, a great mass of data has been incorporated in the chart relative to the oceanic deeps. Thus, not only the seafaring man, but also the geologist, the seismologist, the oceanographer, and scientists in general find much valuable information in the chart.

In pursuance of its policy of increasing the existing knowledge of the ocean's floor, the

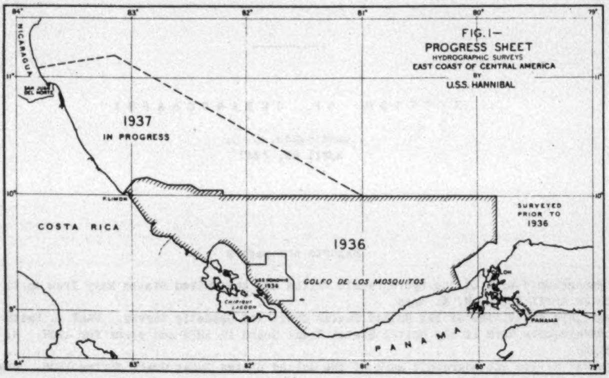

FIG. 1—PROGRESS SHEET HYDROGRAPHIC SURVEYS EAST COAST OF CENTRAL AMERICA BY U.S.S. HANNIBAL

84°
83°
82°
81°
80°
79°
11°
10°
9°
NICARAGUA
SAN JUAN DEL NORTE
1937
IN PROGRESS
P. LIMON
COSTA RICA
1936
SURVEYED PRIOR TO 1936
USS HANNIBAL 1936
CHIRIQUI LAGOON
GOLFO DE LOS MOSQUITOS
COLON
PANAMA
P A N A M A

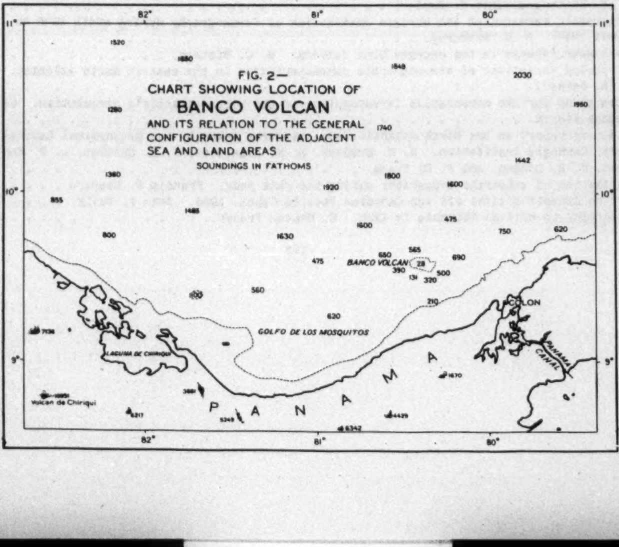

FIG. 2—CHART SHOWING LOCATION OF BANCO VOLCAN AND ITS RELATION TO THE GENERAL CONFIGURATION OF THE ADJACENT SEA AND LAND AREAS

SOUNDINGS IN FATHOMS

82°
81°
80°
11°
10°
9°
1520
1680
1848
2030
1280
1950
1740
1442
1360
1800
1920
1600
855
1485
475
1600
800
1630
750
620
565
680
690
475
BANCO VOLCAN
28
390
500
131
320
100
560
210
620
COLON
GOLFO DE LOS MOSQUITOS
7136
LAGUNA DE CHIRIQUI
PANAMA CANAL
1670
3881
11051
Volcan de Chiriqui
6217
5349
4429
6342
P A N A M A

Hydrographic Office has during the past year conducted hydrographic surveys in the Caribbean Area and continued its dynamic surveys. In addition, it has fostered the interest of navigators in general, with the purpose of obtaining soundings over the vast expanses of unsounded water.

The wide-spread use of the sonic depth-finder and the resultant interest displayed by navigators, both naval and commercial, in exploring the unsounded depths are securing a wealth of information relating to the configuration of the ocean's floor that is of inestimable value to scientists throughout the world.

We feel gratified at the results obtained. Today, through the sonic surveys conducted by the U.S.S. Ramapo in her periodic passages to the Far East, the North Pacific Ocean is becoming as well known as the more traversed oceans. During 1936, on six trips from San Pedro to Manila, the Ramapo added 5527 sonic soundings to the 23,645 soundings obtained on 38 previous passages.

The U.S.S. Hannibal conducted hydrographic surveys on the east coast of Central America from the Atlantic entrance to the Panama Canal as far westward as Port Limon, Costa Rica, covering a total area of 8,000 square miles and a total coast-line of 160 nautical miles. Aerial photographs were utilized in delineating the coast-line and adjacent topography (Fig. 1).

The most interesting investigation undertaken by the Hannibal during the survey of 1936 was the development of a submarine mesa rising from a depth of from 200 to 800 fathoms to a least depth of 28 fathoms, lying about 27 miles northwestward of Colon, Panama (Fig. 2). Inasmuch as the reported position of this bank was well offshore, it was decided to anchor floating signals on the shoal and to determine their positions by simultaneous angles from known shore-stations. Six floating signals, spaced about three miles apart, were anchored, forming a large rectangle over the estimated shoal area, running northwest and southeast. These signals, moored in 30 to 37 fathoms of water, permitted the accurate fixing of the sounding development.

This submarine mesa, located between latitudes 9° 32' and 9° 38' north, and longitudes 80° 19' and 80° 28' west, has an area of 30-1/2 square nautical miles, is oval in shape, rises abruptly from an average general surrounding depth of about 200 fathoms to a least depth of 28 fathoms. On the north side it is almost a sheer cliff rising from 400 fathoms to 40 fathoms in a little over a mile. The profiles indicate that it is somewhat similar in shape to Coseguina Volcano, Nicaragua, thus leading to the assumption that it may be the base of a former volcano. This belief is strengthened by the apparent crest around its rim, and by the deep in its center. Over 2000 soundings, accurately fixed for position, were observed in developing this interesting geological formation. It is proposed to name this feature "Banco Volcan," thus suggesting its probable origin (Fig. 3).

Another item of interest, noted while surveying this bank, was the presence of large schools of fish, in which tuna, mackerel, and barracuda abounded. Apparently this is an untouched fishing-ground in an area where, especially during the rainy season, the fishing is not particularly good.

The U.S.S. Nokomis, in collaboration with a hydrographic commission of Colombian engineers, continued the survey of Colombia as far eastward as Santa Marta, covering a total area of 6000 square miles and a coast-line of 115 nautical miles. Existing charts for this locality so frequently traversed by shipping, were based on Spanish sketch-surveys dating back nearly two centuries. Shipping had to give a wide berth to this entire coast due to the existence of banks, the positions of which were doubtful, and which have now been proved to be greatly in error. With the publication of large-scale coastal charts for this area, navigators will have up-to-date and accurate information, thus reducing steaming time and eliminating the worries resulting from a lack of accurate data (Fig. 4).

This year the Naval survey-expeditions are engaged on an extensive project, namely, the completion of the survey of the north coast of Costa Rica and the extension of the survey of the north coast of Colombia westward from Cartagena to the Colombia-Panama Boundary.

Precise astronomical determinations for latitude and longitude are to be conducted at Port Limon (Costa Rica), San Juan del Norte (Nicaragua), Bluefields (Nicaragua), and Cape Tiburon (Colombia).

Charts from United States Naval surveys--During the year 11 new Hydrographic Office charts, based on original United States Naval surveys, were published.

Echo (sonic) soundings obtained by United States Naval vessels--The following is a tabulated

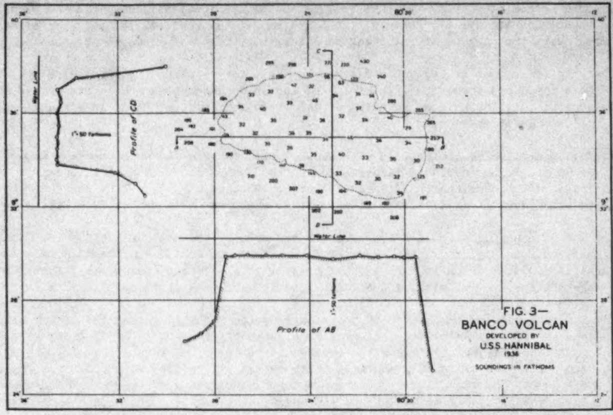
Water Line
Profile of CD
1"=50 Fathoms
C
D
A
B
Water Line
Profile of AB
1"=50 Fathoms
80°20'
9°32'
9°28'
SOUNDINGS IN FATHOMS

FIG. 3—BANCO VOLCAN DEVELOPED BY U.S.S. HANNIBAL 1936

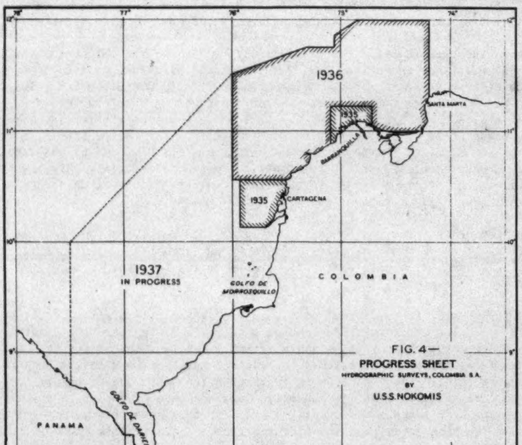
78°
77°
76°
75°
74°
12°
11°
10°
9°
8°
1936
1935
SANTA MARTA
BARRANQUILLA
1935
CARTAGENA
1937
IN PROGRESS
GOLFO DE MORROSQUILLO
COLOMBIA
PANAMA
GOLFO DE DARIEN

FIG. 4—PROGRESS SHEET HYDROGRAPHIC SURVEYS, COLOMBIA S.A. BY U.S.S. NOKOMIS

list of echo (sonic) soundings obtained by United States Naval vessels from January 1, 1936, to December 31, 1936:

U.S.S. Canopus - 214 sonic soundings obtained en route Tsingtao, China, to Weihaiwei and Chinwangtao, China, and return to Tsingtao; then Nimrod Sound to Manila, Philippine Islands; crossing 36° 02' 20" north in 120° 40' east, 39° 43' 40" north in 119° 50' 45" east, and 16° 38' 40" north in 119° 46' 50" east.

U.S.S. Canopus - 325 sonic soundings taken in area of 17° to 18° north latitude and 119° to 120° east longitude where seismic disturbances occurred February 14, 1935.

U.S.S. Hannibal - 384 sonic soundings obtained en route Norfolk Navy Yard to Cristobal, Canal Zone, crossing 33° 06' north in 71° 18' west, 19° 49' north in 75° 10' west, and 9° 39' 30" in 79° 54' 12" west.

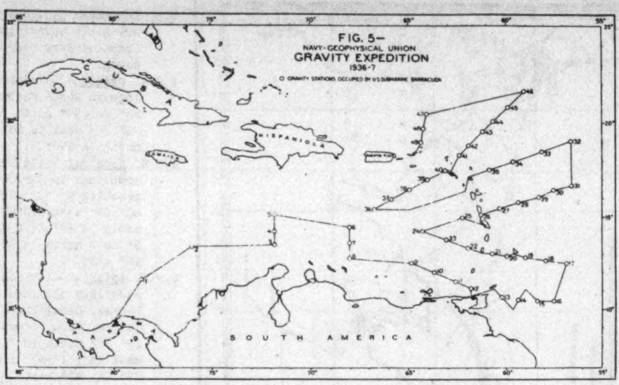

FIG. 5—
NAVY-GEOPHYSICAL UNION
GRAVITY EXPEDITION
1936-7
○ GRAVITY STATIONS OCCUPIED BY U.S.SUBMARINE BARRACUDA

U.S.S. Bushnell - 390 sonic soundings taken en route San Diego, California, to Pearl Harbor, Territory Hawaii, crossing 32° 17' north in 118° 48' 45" west, 25° 57' 30" in 146° 11' 15" west, and 21° 43' 45" north in 156° 40' 30" west.

U.S.S. Hannibal - 33 sonic soundings in Mosquito Gulf in 8° 53'.3 north and 81° 23'.7 west to 9° 55' north and 80° 08'.6 west.

U.S.S. Ramapo - 1368 sonic soundings taken en route Long Beach, California, to Manila, Philippine Islands, crossing 33° 20'.2 north in 130° 22'.8 west, 27° 07' north in 153° 15' west, 20° 22'.7 north in 179° 28'.6 east, and 12° 58'.5 north in 124° 53' west.

U.S.S. Hannibal - 42 sonic soundings in Gulf of Panama at 9° 18' 06" north and 80° 28' 48" west.

U.S.S. Ramapo - 150 sonic soundings obtained while investigating Ramapo Bank in 27° 15' north and 145° 12' east.

U.S.S. Wright - 137 sonic soundings taken while on cruise San Diego, California, to Panama, Republic of Panama, and Galapagos Islands, crossing 25° 41'.2 north in 113° 11'.5 west, 5° 11' north in 79° 57'.5 west, and 2° 04' south in 81° 12' west.

U.S.S. Ramapo - 1132 sonic soundings en route Manila, Philippine Islands to San Pedro, California, crossing 19° 46' north in 122° 47' east, 32° 23'.5 north in 180° 00' east, and 34° 09' north in 123° 21' east.

U.S.S. Hannibal - 300 sonic soundings in Caribbean Sea, north of Panama, in 9° 34'.5 north and 79° 59'.5 west and crossing 9° 11'.5 north in 80° 45' west.

U.S.S. Ramapo - 473 sonic soundings in the Pacific en route San Diego, California, to Balboa, Canal Zone, crossing 30° 48'.4 north in 116° 44'.2 west, 19° 07' north in 106° 30'.6 west, and 7° 16'.5 north in 80° 03' west.

U.S.S. Ramapo - 135 sonic soundings obtained en route Panama Bay, Balboa, Canal Zone, to Guantanamo Bay, Cuba, crossing 10° 34' north in 79° 21' 30" west, 14° 04' north in 77° 44' west, and 18° 57' north in 75° 05'.7 west.

U.S.S. Ramapo - 121 sonic soundings taken en route Guantanamo Bay, Cuba, to Cristobal, Canal Zone, crossing 19° 17' north in 75° 08' west, 14° 33' north in 76° 43' west, and 9° 36' north in 79° 51' west.

U.S.S. Ramapo - 468 sonic soundings en route Balboa, Canal Zone, to San Pedro, California, crossing 7° 02'.3 north in 82° 01'.2 west, 16° 38' north in 101° 39'.5 west, and 32° 21' north in 118° 04'.5 west.

U.S.S. New Mexico - 450 sonic soundings taken en route Panama, Canal Zone, to San Pedro, California, crossing 9° 17' north in 85° 36' west, 80° 40' north in 104° 50' west, and 32° 10' north in 117° 10' west.

U.S.S. Hannibal - 45 sonic soundings obtained in an area near Coco Solo, Canal Zone, in 9° 04' 30" north and 81° 33' 30" west.

U.S.S. New Orleans - 214 sonic soundings in South Pacific, off coast of Peru from 11° 36' 30" south in 81° 51' west to 11° 00' 50" south in 80° 52' 30" west.

U.S.S. Tuscaloosa - 135 sonic soundings in South Pacific, off coast of Peru from 4° 00' south in 82° 58' west to 11° 55' south in 77° 25' west.

U.S.S. San Francisco - 45 sonic soundings along coast of Peru from 5° 00' south in 87° west to 7° south in 81° west.

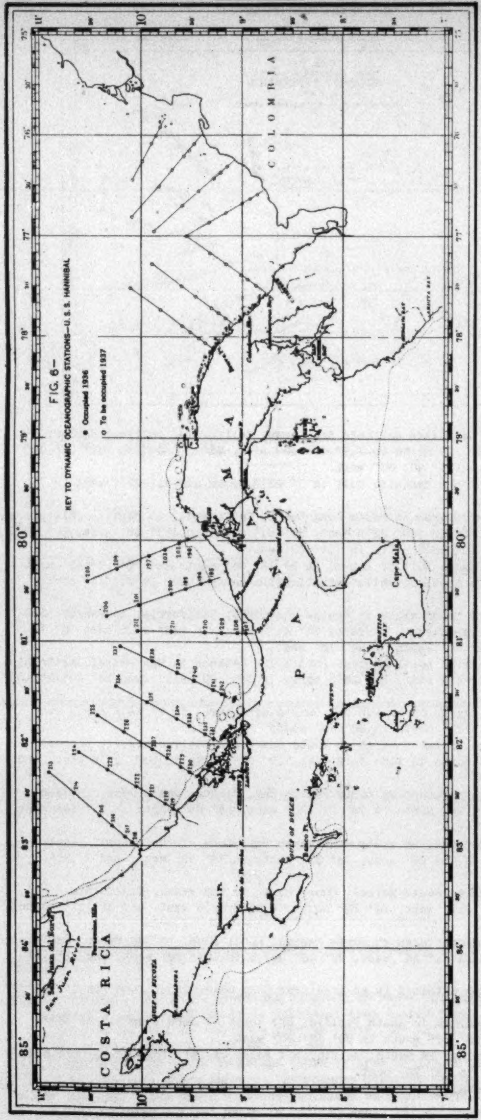

FIG. 6—

KEY TO DYNAMIC OCEANOGRAPHIC STATIONS—U.S.S. HANNIBAL

U.S. Destroyer Squadron Twenty - 209 sonic soundings off coast of Peru near 5° 00' south.

U.S.S. Oglala - 98 sonic soundings in North Pacific from 28° 20' 30" north in 178° 09' 30" west to 26° 36' north in 170° 51' west.

U.S.S. Hannibal - 474 sonic soundings in Caribbean Sea, crossing 9° 33' north in 80° 07' west, 10° 04'.3 north in 82° 57'.2 west and 9° 28'.3 north in 82° 00' 12" west.

U.S.S. Astoria - 147 sonic soundings obtained en route Panama, Canal Zone, to Callao, Peru, crossing 11° 18' 36" south in 78° 44' west and 11° 57' south in 77° 21' 42" west.

U.S.S. Louisville - 130 sonic soundings taken off Callao, Peru, crossing 11° 14' south in 77° 59' 30" west and 12° 04' 48" south in 77° 10' 36" west.

U.S.S. Minneapolis - 30 sonic soundings obtained en route to Callao, Peru, crossing 5° 00' south in 81° 30' west and 12° 00' south in 77° 00' west.

U.S.S. Hannibal - 20 sonic soundings in Caribbean Sea at 8° 56' north in 81° 21' 18" west and 9° 25' north in 79° 56' west.

U.S.S. Hannibal - 46 sonic soundings in Caribbean Sea at 9° 34' 36" north in 80° 21' 06" west and 9° 24' north in 80° 09' west.

U.S.S. Ramapo - 809 sonic soundings taken en route San Diego, California, to Pearl Harbor, Territory Hawaii, and return, crossing 32° 10' 18" north in 119° 15'18" west, 25° 56' 30" north in 145° 18' 18" west, 21° 27' 30" north in 157° 14' west, and return crossing 21° 51' 30" north in 156° 42' 30" west, 27° 22' north in 144° 35' west, and 32° 28' north in 120° 59' west.

U.S.S. Hannibal - 35 sonic soundings in the Caribbean Sea at 9° 35' north in 82° 24' 18" west and 10° 01' 06" north in 82° 50' 30" west.

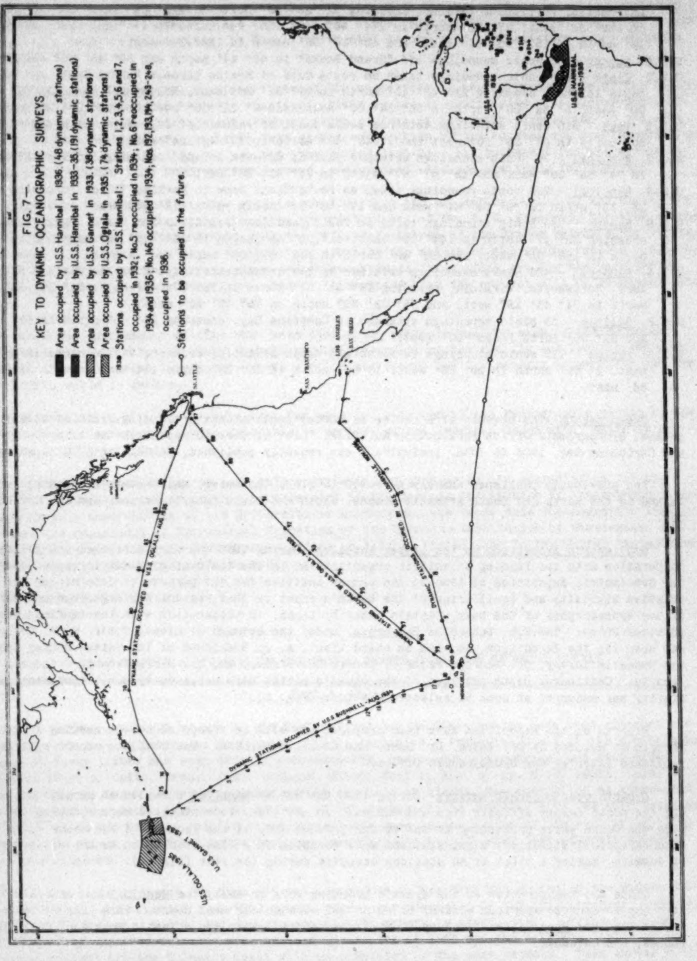

FIG. 7—

KEY TO DYNAMIC OCEANOGRAPHIC SURVEYS

- Area occupied by U.S.S. Hannibal in 1936. (48 dynamic stations)
- Area occupied by U.S.S. Hannibal in 1933-38. (191 dynamic stations)
- Area occupied by U.S.S. Gannet in 1933. (38 dynamic stations)
- Area occupied by U.S.S. Oglala in 1935. (74 dynamic stations)
- Stations occupied by U.S.S. Hannibal: Stations 1,2,3,4,5,6 and 7, occupied in 1932; No.5 reoccupied in 1934; No.6 reoccupied in 1934 and 1936; No.146 occupied in 1934; Nos.192,193,194,243-248, occupied in 1936.
- Stations to be occupied in the future.

SEATTLE
SAN FRANCISCO
LOS ANGELES
SAN DIEGO
HONOLULU
U.S.S. HANNIBAL 1936
U.S.S. HANNIBAL 1933-1938
U.S.S. GANNET 1933
U.S.S. OGLALA 1935
DYNAMIC STATIONS OCCUPIED BY U.S.S. OGLALA - AUG 1935
DYNAMIC STATIONS OCCUPIED BY U.S.S. BUSHNELL - AUG 1934

U.S.S. Porpoise - 414 sonic soundings taken in North Atlantic off coast of United States, West Indies, and Caribbean Sea, crossing 39° 30' north in 69° 30' west, 23° 02' north in 74° 25' west, 16° 51' north in 76° 00' west, and 12° 25' north in 69° 30' west.

U.S.S. Dewey - 30 sonic soundings in Lama Passage, British Columbia, in 51° 58' north and 127° 56' west to 52° 06' north and 128° 08' west.

U.S.S. Nitro - 222 sonic soundings in North Pacific off Cape Mala, from 7° 37' 45" north in 79° 40' west to 6° 31' north in 81° 37' 15" west.

U.S.S. Ramapo - 1258 sonic soundings obtained en route San Pedro, California, to Port Apra, Guam, and Manila, Philippine Islands, crossing 32° 28' 30" north in 120° 09' west, 30° 10' north in 156° 36' west, 27° 33' north in 174° 40' west, 25° 04' north in 174° 26' east, 19° 05' 18" north in 157° 06' 06" east, and 12° 50' 30" north in 125° 38' east.

U.S.S. *Quincy* - 83 sonic soundings off "Grand Banks" in 42° 44' north and 50° 43' 30" west.

U.S.S. *Clark* - 643 sonic soundings taken en route Gulf of Mexico through Panama Canal and Galapagos Islands, crossing 23° 48' 45" north in 89° 02' 30" west, 9° 46' 00" north in 79° 59' 00" west, 5° 32' 00" north in 86° 54' 00" west, and 0° 15' 30" north in 90° 00' 30" west.

U.S.S. *Vega* - 315 sonic soundings obtained south coast of Panama off Cape Mala, crossing 6° 35' 30" north in 83° 05' 00" west and 7° 40' 00" north in 79° 32' 24" west.

U.S.S. *Hannibal* - 76 sonic soundings obtained east of Navassa Island, crossing 18° 18' 18" north in 74° 58' 00" west and 18° 57' 00" north in 74° 40' 30" west.

U.S.S. *Hannibal* - 200 sonic soundings taken en route Canal Zone to Navassa Island, crossing 9° 23' 30" north in 79° 56' 24" west and 17° 53' 00" north in 75° 58' 00" west.

U.S.S. *Ramapo* - 960 sonic soundings taken en route Yokohama, Japan, to San Diego, California, crossing 35° 17' north in 141° 10' east, 41° 02' 48" north in 167° 16' 18" east, 40° 09' 30" north in 159° 02' west, and 33° 42' north in 121° 31' 00" west.

U.S.S. *Hannibal* - 220 sonic soundings obtained en route Guantanamo Bay, Cuba, to Norfolk Navy Yard, Portsmouth, Virginia, crossing 19° 51' 24" north in 75° 07' 42" west, 24° 30' 12" north in 74° 43' 18" west, and 35° 03' 30" north in 75° 02' 00" west.

U.S.S. *Salinas* - 65 sonic soundings obtained in Campeche Bay, crossing 24° 00' north in 88° west and 22° 00' north in 85° 00' west.

U.S.S. *Phelps* - 115 sonic soundings in North and South Atlantic, crossing 7° 19' north in 48° 54' west, 2° 06' north in 39° 56' west, 1° 53' north in 39° 35' west, and 2° 30' south in 38° 54' west.

Ocean depths--The seventh of a series of annual publications presenting lists of oceanic depths, Hydrographic Office Publication No. 210F, "List of oceanic depths in the Atlantic Ocean and Caribbean Sea, 1934 to 1935, inclusive," was recently published, containing 1700 soundings.

The previously published annuals were 210 to 210E, inclusive, which contain soundings obtained in the North and South Atlantic oceans, North and South Pacific oceans, and the Caribbean Sea.

Gravimetric Expedition to the Lesser Antilles--During 1936 the Navy continued its policy of cooperation with the leading scientific organizations in the field of gravimetric exploration. The Gravimetric Expedition of 1936 to the Lesser Antilles for the purpose of determining the relative stability and equilibrium of the Earth's crust in that region, was organized and directed by the Hydrographer of the Navy, Captain Lamar R. Leahy, in cooperation with the American Geophysical Union. The U.S. Submarine *Barracuda*, under the command of Lieut. Comdr. W. A. Gorry, was used for the Expedition, and had on board Lieut. A. J. Hoskinson of the United States Coast and Geodetic Survey, Dr. Maurice Ewing of Lehigh University, and Dr. Harry Hess of Princeton University. Continuous depth-profiles of the ocean's bottom were obtained by sonic equipment, and gravity was measured at some 51 selected stations (Fig. 5).

Reports on the Expedition have been prepared and will be presented at the meeting of the Section of Geodesy by Dr. Ewing, Dr. Hess, and Lieut. Hoskinson. The complete report will be published later by the Hydrographic Office.

Dynamic oceanographic surveys--During 1936 the U.S.S. *Hannibal* occupied 48 dynamic stations off the north coasts of Costa Rica and Panama. In addition, four stations were occupied between Cuba and Colon while proceeding to the survey-grounds and, at the request of the Woods Hole Oceanographic Institution, eight stations were occupied on a line from Colon to the eastern end of Jamaica, making a total of 60 stations occupied during the year (Fig. 6).

Since the inauguration of the dynamic sounding-work in 1933, the *Hannibal* has occupied 248 stations in Central American waters, of which 191 were on the west coast. This year it is expected that the *Hannibal* will occupy 50 stations contiguous to the Atlantic coasts of Costa Rica, Panama, and Colombia.

In furtherance of the request by the President of the National Academy of Sciences, the U.S.S. *Louisville*, on a passage from San Pedro to Pearl Harbor, Territory Hawaii, occupied ten stations on a line closely paralleling one previously run by the *Carnegie*. Dr. E. G. Moberg and R. Doescher of the Scripps Institution of Oceanography, accompanied the *Louisville* and greatly assisted in obtaining dynamic oceanographic data. Upon arrival in Pearl Harbor, the dynamic sounding-equipment was transferred to the U.S.S. *Minneapolis* with the expectation of occupying a line of soundings from Pearl Harbor to San Pedro, but due to inclement weather only one station, in latitude 32° 13' north and longitude 137° 48' west, was occupied (Fig. 7).

The various lines on the chart show the areas in which dynamic surveys have been conducted by United States Naval vessels since this work was commenced in 1933. There is also shown a projected line from the Panama Canal to Hawaii which will be occupied in the future as opportunity affords.

Current- and temperature-charts--Following the completion of the current-charts of the North Pacific Ocean, showing the traverse resultant drifts in the 1° quadrangles, the Hydrographic Office, with a desire to obtain a more comprehensive picture of the water-circulation in the area of the Central American waters, began this year a compilation of the current and sea-temperatures observed on the Atlantic side for the ten-year period 1925-34. All documents for the months of January and October have been examined, coded, and punched, and are now ready for analysis.

The data for the Pacific side will be supplied from the project sponsored by the University of California. This work, under the joint superintendency of Dr. H. U. Sverdrup, Director of the Scripps Institution of Oceanography, and the Officer-in-Charge of the Branch Hydrographic Office, San Pedro, California, was begun in March and embraces the waters of the entire Pacific. All observations of current and surface-temperatures reported to this office for the ten-year period 1925-34, are being examined and coded, and it is expected that the project will be completed this year.

From the vast amount of data thus made available, analysis will be made of the surface-temperatures, currents, and other cognate natural phenomena of the Pacific and Central American waters, and the results incorporated into appropriate charts for the benefit of mariners and the scientific world in general.

In conclusion, I wish to state that the material gathered by the Hydrographic Office in the furtherance of science is always available to members of the American Geophysical Union in connection with their studies.

The Hydrographer wishes to take this opportunity of expressing his appreciation for the splendid cooperation and assistance in this work by the Scripps Institution of Oceanography, the Oceanographic Laboratories of the University of Washington, the Woods Hole Oceanographic Institution, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and by all others assisting the Hydrographic Office to fulfill its mission to the United States Navy, to our country, and to the maritime world.

U. S. Hydrographic Office,
Washington, D. C.

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

Paul A. Smith

The offshore surveys of the United States Coast and Geodetic Survey have been extended during the past year as indicated on Figures 1 to 3, inclusive. Practically all of the hydrography shown on these plates has been done by echo-sounding, radio-acoustic ranging, and taut-wire control (Paul A. Smith, Trans. Amer. Geophys. Union, Part 1, App. A, pp. 9-14, 1935). Some of the hydrography, such as reconnaissance across the Gulf of Alaska, was controlled by astronomic position and dead-reckoning and, of course, is not comparable in accuracy with the work immediately adjacent to the coasts. All of these surveys are made in the course of the regular charting-work of the Bureau, but the unusual features, recently discovered, make them of great interest to oceanographers.

On the Atlantic Coast, an area off the approaches to New York Bay embracing the Hudson Submarine Canyon, and covering over 8000 square miles, was completed by the Oceanographer, Lydonia, Gilbert, and Welker. A detailed description of this survey is given later. During the summer of 1937 it is expected that the area between the survey of 1936 and the northern limits of the surveys of 1933 off the Delaware Coast will be completed by the same vessels. This survey will be extended as far offshore as practicable with the control used, and in addition it is expected that the Delaware Submarine Canyon will be mapped seaward, at least as far as the 1600-fathom curve.

In the Gulf of Mexico, surveys were extended by the Hydrographer, Faris, and Pratt eastward from the eastern limits of the work of 1935 to the Delta of the Mississippi River. During the summer of 1937, work will be continued westward from the general vicinity of Galveston, Texas, joining the work of 1933 and extending over the edge of the coastal shelf.

On the Pacific Coast, the area indicated off the coast of Southern California was completed by the Pioneer, and surveys in the vicinity of Cape Mendocino were extended northward by the Guide, as shown. Both parties will continue in their respective areas during 1937.

The Explorer continued work in Puget Sound. During 1937 she will work in Sumner Straits, Alaska, on new basic surveys of this region.

In Alaska, surveys were continued westward along both sides of the Aleutian Islands by the Surveyor and Discoverer, as indicated, and en route to and from the working grounds reconnaissance-lines were run across the Gulf of Alaska.

The two vessels, Surveyor and Discoverer, will continue work during 1937 in the Aleutian Islands. The Surveyor probably will complete the coastal surveys of Unimak and Unalaska Islands,

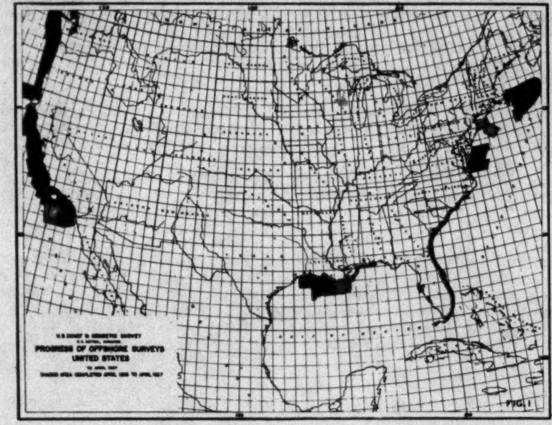
U.S. COAST & GEODETIC SURVEY
R.S. PATTON, DIRECTOR
PROGRESS OF OFFSHORE SURVEYS
UNITED STATES
TO APRIL 1937
SHADED AREA COMPLETED APRIL 1936 TO APRIL 1937

FIG. 1

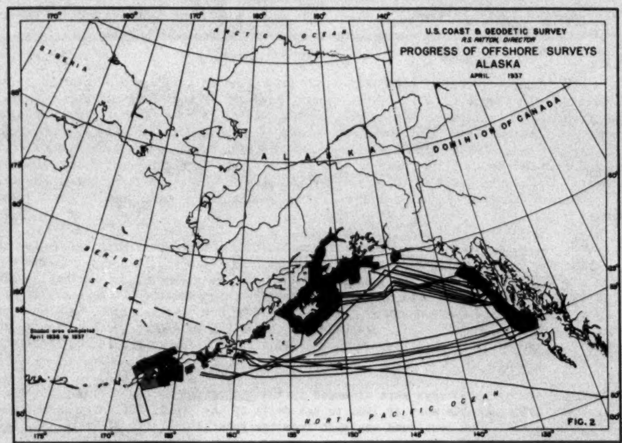
U.S. COAST & GEODETIC SURVEY
R.S. PATTON, DIRECTOR
PROGRESS OF OFFSHORE SURVEYS
ALASKA
APRIL 1937
ARCTIC OCEAN
SIBERIA
ALASKA
DOMINION OF CANADA
BERING SEA
NORTH PACIFIC OCEAN
Shaded area completed April 1936 to 1937
170°
180°
170°
160°
150°
140°
175°
165°
155°
145°
135°
130°

FIG. 2

working westward toward the Islands of Four Mountains Group. The Discoverer will continue surveys of Sanak Islands, the south coast of Unimak Island, and the approaches to Unimak Pass. Both the Surveyor and Discoverer will run additional lines across the Gulf of Alaska, both north and south of the lower group, shown in Figure 2, on their trips to and from the Aleutian Islands.

No additional work was done in the Hawaiian Islands.

In the Philippine Islands, work was continued on the west coast of Palawan Island, and on the northeast coast of Luzon, as shown on Figure 3. The Fathomer, now the only vessel operating in the Philippine Islands, was stranded during a typhoon on August 15, 1936, in the harbor of Port San Vicente. This is a small land-locked harbor on the northeastern extremity of Luzon Island. No lives were lost and the vessel was salvaged without serious damage; however, the accident reduced considerably the annual work of the party. It is of passing interest to note that a barometric reading of 26.96 inches (685 mm), corrected, was obtained at the center of the storm. So far as is known, this is the lowest official reading ever taken in the Philippine Islands. During 1937 work probably will be continued on the west coast of Palawan.

A typical example of the surveys of the coastal slopes is given in Figure 4, showing the survey of 1936

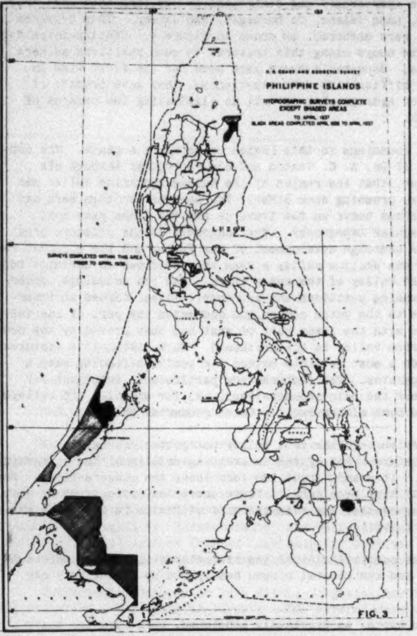
U. S. COAST AND GEODETIC SURVEY
PHILIPPINE ISLANDS
HYDROGRAPHIC SURVEYS COMPLETE EXCEPT SHADED AREAS
TO APRIL 1937
BLACK AREAS COMPLETED APRIL 1936 TO APRIL 1937
LUZON
SURVEYS COMPLETED WITHIN THIS AREA PRIOR TO APRIL 1936

FIG. 3

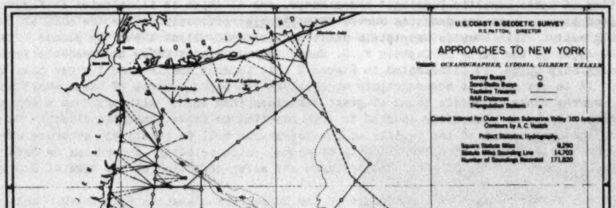
U.S. COAST & GEODETIC SURVEY
R.S. PATTON, DIRECTOR
APPROACHES TO NEW YORK
Vessels: OCEANOGRAPHER, LYDONIA, GILBERT, WELKER
Survey Buoys
Sono-Radio Buoys
Traverse
R.A.R. Distances
Triangulation Stations
Contour Interval for Outer Hudson Submarine Valley 100 fathoms
Contours by A. C. Veatch
Project Statistics, Hydrography
Square Statute Miles 8,290
Statute Miles Sounding Line 14,703
Number of Soundings Recorded 171,820
LONG ISLAND
Hydrography within this line completed May to October 1936
OUTER HUDSON RIVER SUBMARINE VALLEY

FIG. 4

of the approaches to New York. The inshore hydrography was controlled by a combination of visual fix-positions on buoys, taut-wire traverse, and radio-acoustic ranging. The sounding was done with the Dorsey Fathometer. The offshore hydrography was controlled by the long taut-wire traverse from the vicinity of Moriches Inlet, Long Island, to Barnegat, New Jersey. This traverse determined the positions of buoys, which were anchored, as shown in Figure 4. Station-ships for radio-acoustic ranging were located at the buoys along this traverse in such positions as were necessary for the work in the outer areas. Sono-radio buoys were used for the first time in actual hydrography and, while some minor difficulties were experienced, they gave promise of greatly reducing the costs of this type of hydrography, as well as eliminating the hazards of using station-ships for this type of work.

It is impossible to show the actual soundings in this region on so small a plate. The contours shown represent the interpretation of Dr. A. C. Veatch and are reproduced through his courtesy. It should be mentioned, however, that the region of the Hudson Submarine Valley was surveyed by two systems of sounding-lines, crossing each other. The control for this work was shifted from time to time between the various buoys on the traverse and the lines gave most satisfactory crossings, even in this irregular topography. The soundings in the offshore area were taken by the ordinary fathometer. A thorough development of the Valley and the adjacent regions was made and the survey shows that the shallow valley across the shelf has no definite topographic connection with the deeper eroded valley of the outer reach. The old soundings, based on inaccuracies of locations by dead-reckoning positions and astronomic fixes, forced an interpretation which gave a pronounced S-shape to the outer canyon and connected the part of the valley immediately below the 50-fathom curve with the lower part of what has been proved by the new survey to be an entirely different submarine valley to the northward. Such distinctive features as these, when charted accurately, provide a most reliable method for position-finding when a vessel is equipped with echo-sounding apparatus. The features are particularly important for this purpose when they are found in or near the main steamer-lanes, as, for example, the valleys on the southern edge of Georges Bank, and some of the Pacific Coast submarine valleys.

In the Gulf of Mexico a large depression, similar to a valley but probably orogenic in origin, was found. Figure 5 shows this feature. One of the interesting details of the topography in this area is the small dome indicated. It stands about 165 feet above the ocean's floor. The bottom-specimens obtained on these usually have been coral. There are other indications of what may be similar lumps along the edge of the coastal shelf in the Gulf of Mexico in the areas which have been surveyed during the past three years.

The examples mentioned illustrate the possibilities of the new methods of hydrographic surveying. The work on the coastal shelves and the coastal slopes has opened up an entirely new and unexplored region.

During the summer of 1936 sono-radio buoys, as previously mentioned, were used for the first time in radio-acoustic ranging. These buoys, one of which is illustrated in Figure 6, with the United States Coast and Geodetic Survey Ship Lydonia, obviously reduce the cost of this type of work greatly. This buoy is completely self-contained and weighs about 750 pounds. Another type developed by the party of Captain F. H. Hardy, United States Coast and Geodetic Survey, commanding Ship Guide, is illustrated in Figure 7. It is much smaller and lighter than the former. It is obvious that oceanographic expeditions can carry several of these buoys and use them to survey banks or shoals found at great distances from land. Although such a survey will not necessarily be as accurately located in true position as those connected directly to shore-control, the development of the details of the topography will be relatively accurate when controlled by surveys, based upon the velocity of sound, which velocity in turn can be determined from physical observations of water-temperatures and water-densities at the time of survey.

Mention should be made of the success of the Dorsey (shoal-water) Fathometer. This instrument was used throughout the summer of 1936 by the Hydrographer and Lydonia, and its performance has more than met all expectations. As an example of the accuracy of the instrument, in 552 square miles of hydrography run by the Hydrographer off the Gulf Coast of Louisiana there were 550 crossings of the system of sounding-lines with no one of these crossings differing by more than one foot. The maximum depth sounded in the area mentioned was 75 feet and the minimum was 23 feet. The practical limit of depth to which this instrument can be used is about 40 fathoms; however, it has been so successful that this summer a new type of fathometer will be tried. It is based upon the same principles, but is not limited to shoal water, and it should greatly increase the accuracy of sounding in deeper water--1000 fathoms or more.

Primary tide-stations for hydrographic and geodetic control and for general tidal information were continued at 50 localities, distributed as follows: Twenty-five on the Atlantic

Coast, five on the Gulf of Mexico, 15 on the Pacific Coast, four in Alaska, and one in the Territory of Hawaii.

A tidal survey of San Francisco Bay is in progress. Observations covering a period of one year are being obtained at 11 stations and shorter series at a number of additional stations. It is planned to expand this survey to include the Sacramento and San Joaquin rivers.

A special tidal survey of Delaware Bay, in cooperation with the State of Delaware, was continued with the maintenance of three standard stations. A fourth station is to be established soon.

A special tidal survey of Galveston Bay is now in progress in cooperation with the United States Engineer Office. Five gages are now in operation.

The survey of Barnegat Bay, in cooperation with the State of New Jersey, has been completed.

The tide- and current-survey of Los Angeles and Long Beach Harbors, conducted for the purpose of investigating the seiche- and surge-movements of these harbors, was completed.

Through a cooperative arrangement with the Lighthouse Service, hourly current observations covering periods of two years and one and one-half years, respectively, were completed at Stone Horse Shoal Lightship, Massachusetts, and Barnegat Lightship, New Jersey. Similar observations were obtained at Ambrose Channel Lightship and Scotland Lightship in the approach to New York Harbor. At each of these two lightships the series covered seven months.

Current-observations in York River, Virginia, are being secured in cooperation with Bureau of Fisheries. Beginning in August, 1936, several days of observations have been obtained each month.

In addition to the current-work just mentioned, series of current-observations were secured at numerous locations offshore and in inland waterways by our hydrographic parties and through cooperative arrangements with other organizations.

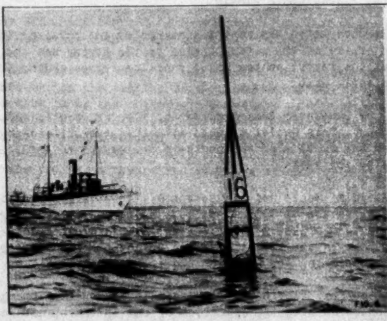

FIG. 6—SONO-RADIO BUOY WITH SHIP LYDONIA

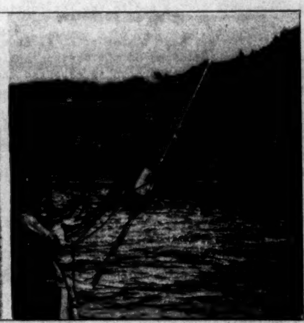

FIG. 7—SONO-RADIO BUOY USED BY SHIP GUIDE PACIFIC COAST

A special publication dealing in a comprehensive manner with currents in Narragansett Bay, Buzzards Bay, and Nantucket and Vineyard sounds was issued in December, 1936.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE OCEANOGRAPHIC WORK OF THE UNITED STATES COAST GUARD IN 1936 AND PLANS FOR 1937

R. R. Waesche

In 1936 the United States Coast Guard assigned two first-class cruising cutters, the Pontchartrain and Champlain, to the duties of the International Service of Ice Observation and Ice Patrol in the North Atlantic Ocean. The 125-foot patrol boat General Greene was designated as the oceanographic vessel of the Ice Patrol Force. The ice-observation officer, who has charge of the scientific work on the patrol cutters was Lieutenant G. Van A. Graves, and the oceanographer in charge of the scientific work on the oceanographic vessel was Floyd M. Soule. As in past years, several thousand temperature-reports were received from passing steamers, thus enabling the ice-observation officer to maintain an up-to-date surface isothermal chart of the usually ice-infested area in the vicinity of the Grand Banks. From these data six fortnightly sea-surface isothermal charts were prepared and will appear in Coast Guard Bulletin No. 26 which is now in press.

Although the ice-season of 1936 was unusually light and did not necessitate the inauguration of the Ice Patrol, the General Greene spent the months of April, May, and the first part of June supplying dynamic topographic charts of the Grand Banks Region to the patrol cutters. During this period three current-surveys of the critical area were made to a reference-level of 1000 decibars, although the temperature- and salinity-measurements extended in many cases to a depth of 1400 meters where the depth of water permitted. In this work 187 oceanographic stations were occupied.

Throughout the season the Labrador Current flowed with greater than average volume and with a mean temperature somewhat lower than average, although the minimum temperature was decidedly warmer than usual. These conditions were attributed to the excessive volume of flow and heat-transfer of the West Greenland Current in 1935.

Upon the conclusion of the ice season, the General Greene made an abbreviated post-season cruise, occupying 30 additional oceanographic stations from surface to bottom during the interval June 20-26, 1936. These stations were disposed in the form of two sections, one extending from South Wolf Island, Labrador, to Cape Farewell, Greenland, and the other from 60° 09' north latitude and 51° 15' west longitude, to the mouth of Arsuk Fiord, Greenland. At this time the glacier front in Arsuk Fiord was visited and photographed as in 1928, 1931, and 1933. This time the various distances of retreat and advance were measured by means of numerous horizontal sextant-angles taken from both ends of a 600-foot base-line. On the post-season cruise 295 fathometer-soundings were taken. These have been corrected, tabulated, and supplied to the United States Hydrographic Office and to the International Hydrographic Bureau.

During the year Commander F. A. Zeusler completed his report summarizing the physical investigation conducted on the oceanographic cruise of the cutter Chelan in the Bering Sea and Bering Strait in 1934. It is expected that the report on the results of the corresponding chemical investigation will be completed at an early date.

Coast Guard Bulletin No. 19, Part II, by Commander Edward H. Smith, Floyd M. Soule, and Olav Mosby, has been completed and is now in press. This Bulletin deals with the physical oceanography of the Labrador Sea and is based chiefly on the results of the northern cruises of the Marion in 1928 and of the General Greene in 1931, 1933, and 1934.

Also in press is Bulletin No. 26 by Floyd M. Soule and Lieutenant G. Van A. Graves. This Bulletin covers the results of the Ice Patrol season of 1936 as well as a discussion of the results of the post-season cruises of 1935 and 1936 of the General Greene, the seasonal fluctuations in volume of flow of the Labrador Current in the vicinity of the Grand Banks, and the phenomenon of the lateral mixing along the boundaries of the Labrador and Atlantic currents.

The oceanographic work planned for the current year naturally includes the dynamic topographic surveys of the Grand Banks Region in connection with the operation of the International Ice Patrol. At present the General Greene is engaged in the work of supplying current-maps to the patrol cutters as in previous years. This year it is intended that the General Greene will make a post-season cruise which will include four sections across the Labrador Current, four sections across the Atlantic Current, and one section across the West Greenland Current with the field of operations extending from the Tail of the Grand Banks to Cape Farewell, Greenland.

U. S. Coast Guard,
Washington, D. C.

APPENDIX A--THE OCEANOGRAPHIC WORK OF THE UNITED STATES COAST GUARD DURING 1936

Edward H. Smith and
Floyd M. Soule

In addition to the field-work which the United States Coast Guard carried out in 1936, and which has been reported in the report above, this same year also has witnessed the completion of the written report on the oceanographic observations of several Coast Guard expeditions to Baffin Bay and Labrador Sea. This report (United States Coast Guard Bulletin No. 19, Part 2) is now in the printer's hands for final publication. A few preliminary remarks on some of the conclusions reached in the above investigation are of general interest to physical oceanographers dealing with problems in the northern North Atlantic.

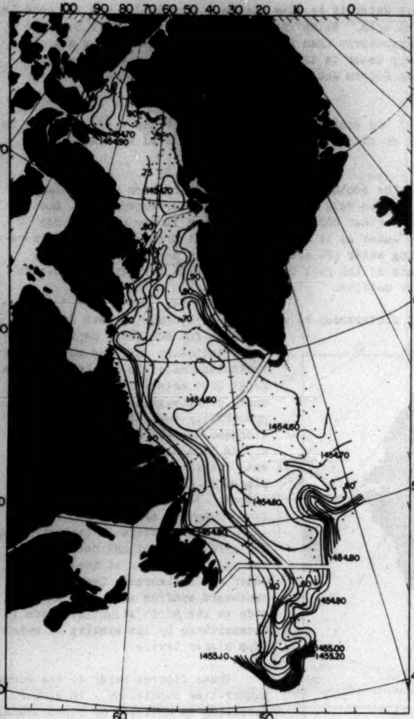

FIG. 1—DYNAMIC TOPOGRAPHY, 1500-0 DECIBAR SURFACE, NORTHWESTERN NORTH ATLANTIC, (COMPOSITE 1928-35)

The surface-circulation of the Labrador Sea (Fig. 1) is summarized as follows: The East Greenland Arctic Current and western branch of the Irminger Current on rounding Cape Farewell are renamed the West Greenland Current which flows northwestward. The West Greenland Current branches, part crossing Davis Strait Ridge into Baffin Bay and a part flowing westward south of the Davis Strait Ridge and joining Arctic water flowing southward out of Baffin Bay to produce the Labrador Current. The Labrador Current, composed of about three parts west Greenland water to two parts of Baffin Bay water, flows southerly along Labrador and Newfoundland and the eastern edge of the Grand Banks, eventually turning in a general northeasterly direction along the northwestern borders of the Atlantic Current. From the northern edge of the Grand Banks to the Tail of the Banks parts of the Labrador Current are turned back to the northward. The northernmost of these returned branches forms a closed whorl between the trunk of the Labrador Current, Flemish Cap, and mixed waters of the borders of the Atlantic Current, which water flows northward and eastward extending as far as 55° north.

The general distribution of the temperature and salinity follow what one might expect from an inspection of the surface-circulation.

Temperature-salinity correlation of the subsurface observations indicate that the Labrador Sea is characterized by four classified types of water. The Surface Water to a depth of 100 or 200 meters is identified by a wide range in temperature and the lowest of observed salinities. From about 500 meters to about 2000 meters the Labrador Basin is occupied by Intermediate Water, the deeper limit of which is characterized by a temperature of 3° C, and a salinity of about 34.90 o/oo. This Intermediate Water is considered to lie below the Surface Water and offshore of the more rapid currents. The Intermediate Water is in slow cyclonic circulation and its core is found in a salinity minimum of about 34.88 o/oo. Below the Intermediate Water is to be found the Deep Water characterized by lower temperatures than the Intermediate Water and by salinity maxima of about 34.94 o/oo. Below the Deep Water is to be seen a small amount of Bottom Water with temperatures of less than 2° C. This Bottom Water is in very slow cyclonic circulation with a generally southern direction.

Several computations of the volume of the exchange of the above-described types of water in the Labrador Sea have shown that there is an excess of inflow over outflow of approximately 2,000,000 cubic meters per second.

The position of saltiest water along the southwest coast of Greenland when plotted against depth, according to Coast Guard observations as well as those of two other expeditions, show that as the Irminger Atlantic Water flows farther and farther northward in the Labrador Sea it progressively sinks. This sinking of the water as it mixes in the West Greenland Current is regarded as cabbeling. Such areas of sinking water are often referred to as polar fronts, and this one in the upper levels along the path of the West Greenland Current largely explains the previously mentioned excess of inflow over outflow.

A consideration of the departures of differences of anomalies of dynamic heights from averages for 500-meter depth intervals, indicates that the most nearly motionless water in the Labrador Sea is at 2000 meters. Because of the small density-gradients and the probability that no absolutely motionless surface exists and because of its undulatory character if it does exist, no great reliance is placed on the resulting absolute values. The indicated directions of flow, however, are believed reliable and also instructive in demonstrating the circulation of the deeper water. The cyclonic motion of the Deep Water of the Labrador Sea permits a southward outflow along the American side to the North Atlantic, which is necessitated by the sinking of water from higher levels.

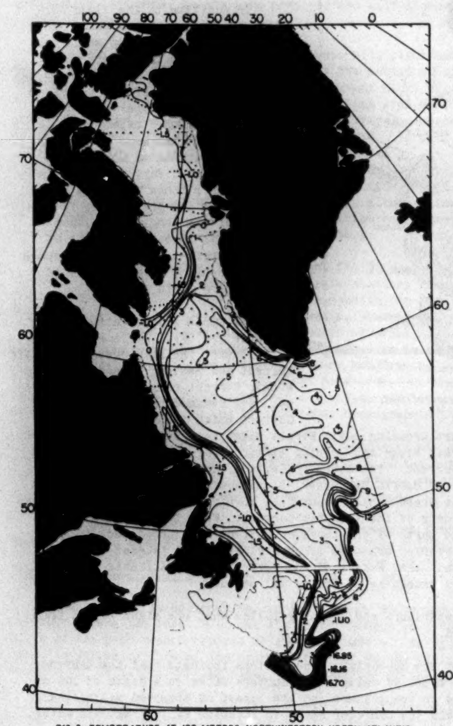

FIG. 2—TEMPERATURE AT 100 METERS, NORTHWESTERN NORTH ATLANTIC, 1928-35

These figures refer to the normal summer-time conditions. In winter, cabbeling is assisted by convectional cooling, the extent of which in the Labrador Sea has been a subject heretofore of considerable speculation. The low-temperatured Bottom Water of the Labrador Sea (according to the Coast Guard's observations) is always separated from the cold parts of the West Greenland and Labrador currents in summer by water of higher temperature. The Bottom Water, therefore, is either a result of winter-time convectional cooling or is a relic of conditions which no longer exist. That the latter is not true is proved by the distribution of dissolved oxygen; six or seven cubic centimeters per liter found in the deeper parts of the Labrador Basin indicates quite strikingly the presence of active mixing, with no water there but what has been recently at the surface.

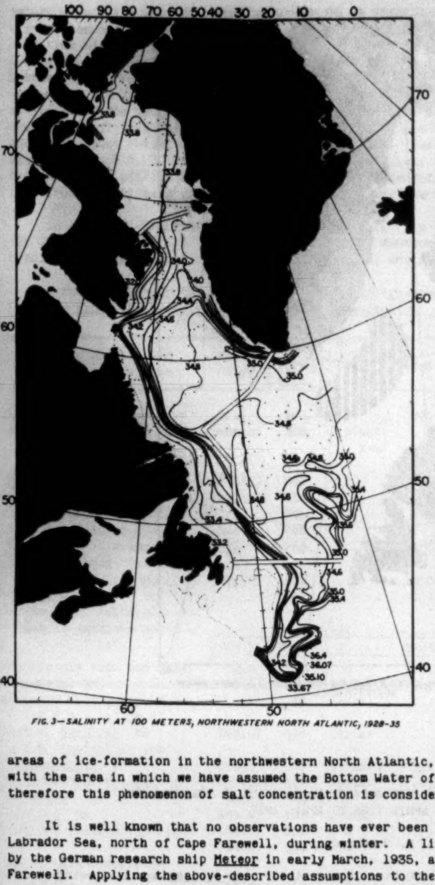

FIG. 3—SALINITY AT 100 METERS, NORTHWESTERN NORTH ATLANTIC, 1928-35

Lacking subsurface observations from the Labrador Sea north of Cape Farewell during winter, the summer-time observations of the Coast Guard have been employed to determine the extent of convectional cooling, assuming certain empirical winter-time conditions to exist. For example, if complete stagnation of the central portions of the Labrador Sea north of Cape Farewell be assumed, the maximum temperature at which vertical convection to the bottom can occur may be found from the average salinity of the water-column and the density of the Bottom Water observed in summer. Subjecting the observational data to these requirements (approximate ranges of 2° C to minus 1.8 C in temperature, and 34.81 o/oo to 34.91 o/oo in salinity) there is revealed a certain area in the central region of the Labrador Sea in which water, cooled during winter, sinks to the bottom. That this is the supply for much of the Bottom Water of the northern North Atlantic, rather than the cold surface-currents across Davis Strait Ridge, is proved likewise by similar computations of the average salinity and maximum density around the margins of the Labrador Sea. Temperatures very close to freezing, combined with the low salinity of the water, eliminate these belts as a source of supply.

An increase in the density through an increase in salinity resulting from ice-formation is a factor which assists winter-time convectional sinking in some regions (see Helland-Hansen and Nansen, 1909, and Mosby, 1934). The areas of ice-formation in the northwestern North Atlantic, however, are largely non-coincident with the area in which we have assumed the Bottom Water of the Labrador Sea to originate, and therefore this phenomenon of salt concentration is considered inconsequential there.

It is well known that no observations have ever been taken from the central parts of the Labrador Sea, north of Cape Farewell, during winter. A line of stations, however, were occupied by the German research ship Meteor in early March, 1935, along a line running south of Cape Farewell. Applying the above-described assumptions to the Meteor's data, temperatures at two stations south of Cape Farewell between the Irminger Current and the Atlantic Current (at depths of 725 and 1650 meters, respectively) were actually found lower than the maximum temperature necessary to produce vertical convection to those depths. In our opinion, therefore, shortly prior to the Meteor's observations vertical convection in this region extended to depths of about 2000 meters.

Although the above conclusions are based upon several hypothetical assumptions and definite final confirmation awaits further surveys when subsurface observations must be made during the coldest time of winter, it is believed nevertheless that an important source of the Bottom Water of the northern North Atlantic Ocean has been found and charted.

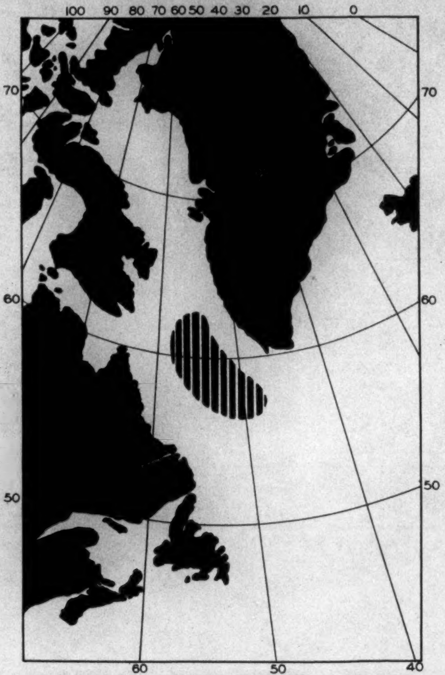

FIG. 4—SHADED AREA INDICATES WHERE BOTTOM-WATER IS FORMED DURING WINTER-TIME

U. S. Coast Guard,
Washington, D. C.

OCEANOGRAPHIC RESEARCH AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1936 TO APRIL 1937

H. U. Sverdrup

Research vessel--On November 13, 1936, the Institution's boat *Scripps* was lost owing to explosion and fire. Two men were badly injured, one died a week later and the other is still in the hospital. In order to replace the *Scripps*, Robert P. Scripps bought on April 5, 1937, a 104-foot auxiliary schooner which, after remodelling, he will give to the Institution. The new vessel will, in addition to the crew, accommodate a scientific party of six, will contain good laboratory space, and will carry three winches for oceanographic work.

Expeditions and oceanographic data--Until November 13, 1936, the *Scripps* undertook a series of short cruises, during which a total of 22 stations were occupied. Dr. L. H. Miller accompanied the *Scripps* on some of these trips to study marine birds. In June, 1936, Martin W. Johnson accompanied the United States Coast and Geodetic Survey ship *Guide* on a cruise in the region off Cape Mendocino where five stations were occupied. In November and December, Dr. E. G. Moberg and R. N. Doescher accompanied the U.S.S. *Louisville* from San Pedro to Pearl Harbor, Hawaii, and returned on the U.S.S. Minneapolis, occupying 11 stations en route. An investigation of the circulation and oceanographic conditions off the southern California coast is in progress in cooperation with the California Fish and Game Commission. The program consists of a study of the hydrographic conditions to be undertaken by the Scripps Institution and the release of 6000 drift-bottles by the Fish and Game Commission. The boat Bluefin of the Commission is being used for the work. The area to be investigated is bordered by the mainland and extends about 170 miles out to sea. The hydrographic stations are located upon four sections extending normal to the coast, one off Port San Luis, one off Santa Barbara, one off San Pedro, and one off San Diego. There are about seven to nine stations on each line. Between March 25 and April 3, 1937, on a cruise in which R. H. Fleming and H. Nakamura took part, 27 of the stations were occupied. Two thousand drift-bottles were released, from which some returns have already been received. Similar cruises will be undertaken in the middle of May and at the end of June.

In addition, the Institution has received data from other sources, of which 30 series from the Caribbean Sea (U.S.S. Hannibal) is especially mentioned. Table 1 contains a summary of the oceanographic data received between April 1, 1936, and April 1, 1937.

Table 1--Number of observations of sea-temperatures, salinities, and meteorological conditions received at the Scripps Institution, April 1, 1936, to April 1, 1937

Station or ship and number of stations	Salinity	Temperature	Depth	Wind	Air-temperature	Remarks
			meters			
Scripps Institution Pier	365(a)	365	0	365	365	Continuous barograph- and pyrheliometer-records and daily observations of humidity and precipitation
Scripps Institution Pier	365(a)	365	5(bottom)	...	...	
Balboa Pier	365(a)	365	0	365	...	
Hueneme	313(a)	313	0	313	...	
Pacific Grove	365	365	0	365	...	
Farallon Islands	365(a)	365	0	...	...	
Blunts Reef Lightship	365(a)	365	0	365	...	
U.S. Lighthouse Tenders, Sequoia and Lupine,	200(a)	1400	..	1400	1400	Water thermograph-records for all coastal trips of Lupine
Santa Cruz	...	111	..	111	...	
Grace Line, Valparaiso to Central American ports	...	3470	..	...	3470	Also rainfall-data
Totals	2703(a)	7484	..	3284	5235	
California Fish and Game,	72(b)	72	0	...	...	San Diego to Gulf of Calif.
Bluefin, 27	350(b)	350	serial	...	...	Off southern California
U.S.C.G.S.S. Guide, 5	50(b)	50	serial	...	...	Off Cape Mendocino
U.S.C.G.S.S. Guide, ?	...	...	0	...	...	?
U.S.S. Hannibal, 30	383(b)	383	serial	...	...	Caribbean Sea
U.S.S. Louisville and Minneapolis, 11	177(b)	177	serial	...	...	Between southern California and Hawaiian Islands
U.S.C.G.S.S. Pioneer, ?	127(b)	127	serial	...	...	Off southern California
Reliance	48(b)	48	0	...	...	San Diego to Panama
Scripps, 22	433(b)	433	serial	...	...	Off southern California
Scripps Institution Pier	104(b)	104	0	...	...	
	104(b)	104	5	...	...	
Yacht Zaca (Templeton Crocker)	72(b)	72	0	...	...	San Diego to and into Gulf of California
Totals	1920(b)	1920	..	...	...	

Notes: (a) = salinity by specific gravity; (b) = salinity by chlorine-titration.

Physical oceanography and maritime meteorology--Dr. H. U. Sverdrup studied the evaporation from the ocean by computing upwards transport of water-vapor by eddy-conductivity, making use of laboratory results concerning turbulence over a rough surface and of measurements of humidity-gradients undertaken on board the Atlantis. Dr. George F. McEwen reports that averaging and plotting by months and quadrangles of sea-surface temperatures reported from various steamers was continued. A meteorological summary of data from Scripps Pier was completed, comprising observations from July, 1924, to January, 1937, covering maximum and minimum air-temperatures, mean air-temperatures, wet- and dry-bulb temperatures, dew-point, relative humidity, vapor-pressure, wind, and weather by days. Included also were solar-radiation observations since 1928 and monthly summaries of the above data.

A relief model was prepared from the topographic map of the ocean-floor and adjacent land along the coast of San Diego County completed in 1935. A topographic map of the ocean-floor and some adjacent land along the eastern coast of Santa Barbara County was more than half completed. The area included is about 30 miles east and west and 20 miles north and south (latitude 34° 10' to 34° 30', longitude 119° 14' to 119° 50'). The Works Progress Administration project, sponsored in 1935 by the University of California, for evaluating oceanographic data reported by ships since 1924, and begun under the general superintendency of the Director of the Scripps Institution and the Officer-in-Charge of the Branch Hydrographic Office in San Pedro, has continued.

In the summer of 1936, Dr. R. T. Young of Worcester Polytechnic Institute, Worcester, Massachusetts, developed a water-proof mounting for a Westinghouse "Photox" electric cell (type SW-30), so that the cell could be lowered into the water to measure subsurface light-intensities in the ocean. By simultaneously measuring the current obtained from a second "Photox" placed on top of the boat, sufficient data can be obtained for calculating the absorption-coefficient. R. D. Gordon is at present engaged in calibrating the cells; after this is completed, the ten series of field-data, already obtained and taken at 5-meter intervals to depths of 50 meters, will be computed and a report published.

During the summer and fall of 1936, intensive tests were made by N. W. Cummings, aided later by Mr. Gordon, of the use of the Burt Phototube for recording solar-radiation intensities (see N. W. Cummings, Trans. Amer. Geophys. Union, 1935, pp. 515-519, for description of instrument).

Studies were made by Dr. McEwen of certain energy-relations in the zone of contact between the ocean and the atmosphere. Calculations were made of "normal" monthly sea-surface temperatures at intervals of 1/2-degree latitude from selected averages by months and 5-degree quadrangles compiled for the North Pacific by the staff of the Imperial Marine Observatory, Kobe, 1911-1930. Deductions were made from these results and local observations of the vertical temperature-gradient, together with the distribution of solar radiation, the amount of radiation penetrating the sea-surface, and the resulting evaporation from the sea.

Improvement and experimental application of former methods of calculating surface-currents from surface-temperature, and revision of values of fundamental factors of this problem were carried out by Messrs. McEwen and Gordon. Continued investigations were undertaken of trends of temperature of air and sea-surface corresponding to the Southern California Area with the purpose of providing advance temperature-indications. Investigations of advance indices of Pacific coastal seasonal rainfall continued. Many inquiries received regarding these investigations show continued interest in them.

In a study of Halvorson and Ziegler's tables (J. Bact., v. 25, pp. 101-121, 1932) for computing "most probable" bacterial populations from the results of successive tenfold dilutions of the sample, C. E. ZoBell noted (by checking with other methods) that their values were consistently too high. Assuming _à priori_ uniform arithmetical distributions of population-values and applying Baye's principle of inverse probability, Mr. Gordon reproduced their formula which gives the mode of Baye's _à posteriori_ distribution on this assumption. Gordon considered that, while the mode of a distribution does represent a "most probable" (or most frequent) value of its variable, this value is not necessarily the value subject to the least probable error. Messrs. Gordon and McEwen have developed formulas for computing the geometric means of these _à posteriori_ distributions, as well as their logarithmic standard deviations. It is believed that this application of Baye's principle is legitimate. Results will be published after experimental verification, including tables which are to be calculated from formulae thus derived.

R. H. Fleming has examined data collected by the _Scripps_ during recent years in order to determine the nature of seasonal changes in the water off the Southern California Coast, and also to identify the types of water present. Dynamic computations were made for a number of the stations located off San Diego. His studies on material collected off the Pacific Coast of Central America by the U.S.S. _Hannibal_ were continued. Dynamic computations on the data from the Gulf of Panama were completed. Mr. Fleming cooperated with Mr. Woodrow Jacobs of the United States Weather Bureau in developing a method for the determination of atmospheric chlorides. Mr. Jacobs has published two reports on this work.

Chemical investigations--As part of a long-established chemical program, routine determinations of the chloride, phosphate, silicate, titratable base, and hydrogen-ion content were made on water-samples collected from the surface and from near the bottom at the end of the Institution's pier. Water-samples collected by the _Scripps_ were analyzed for the same constituents and also for dissolved oxygen, calcium, and sometimes for total carbon dioxide and atmospheric nitrogen. Dissolved-oxygen determinations were also made on all of the samples collected by the United

States Coast and Geodetic Survey Guide off Cape Mendocino, by the U.S.S. Louisville and Minneapolis between Southern California and the Hawaiian Islands, and at 27 stations occupied by the M.V. Bluefin of the California Division of Fish and Game from the coast of Southern California to a distance of about 500 miles offshore. On many of these samples, calcium and titratable base was also determined.

During the summer of 1936 temporary student-workers made it possible to continue investigations previously begun and also to initiate new lines of research. For example, further studies of the buffer mechanism of sea-water were made (John Lyman, University of California, Berkeley); methods for detecting small differences in the carbon-dioxide content of the air that may be correlated, along the coast, with the direction of the wind (Gilbert Hofeller, California Institute of Technology); and a rapid and sensitive method for determining arsenic was applied to sea-water (Theodore Winnick, University of California, Berkeley).

With the assistance of Works Progress Administration workers, numerous determinations of the fixed nitrogen-content of bottom-samples from various parts of the Pacific were made, a number of water-samples were analyzed for organic and ammonia nitrogen for calcium and, by means of the Van Slyke blood gas apparatus, for dissolved gases including nitrogen. Various methods for determining iodine in sea-water were tried and it is thought that by means of one of these methods accurate information regarding the iodine-content of a number of samples not only from the surface but from various depths down to about 1000 meters was obtained. A study of methods for the determination of manganese and iron in sea-water has also been begun.

Marine microbiology--The observations of Claude E. ZoBell on several bottom-sediment samples from the Channel Island Region off the coast of Southern California reveal that there are several types of bacteria which influence the state of oxidation or reduction, as well as the pH of bottom-deposits. Mud-inhabiting aerobic bacteria are capable of lowering the potential to E_h - 0.26 volt, and anaerobes have been recovered from the sediments which reduce the potential to E_h - 0.63 volt in the presence of available organic matter. A new vacuum-tube potentiometer and a measuring technique which can be used at sea have been perfected.

Assisted by Sydney C. Rittenberg, a micro-asbestos calomel half-cell has been prepared for measuring the O/R potentials of anaerobes in oval tubes. The device makes it possible to study the influence of bacteria upon the O/R potential and also to study the influence of O/R potentials upon the activity of the bacteria. Jointly with D. Q. Anderson, an oval-tube method has been described for the enumeration of marine anaerobes which permits the duplication of results with a standard deviation not exceeding seven per cent. Application of the method shows that 10 to 20 per cent of the bacteria in sea-water are anaerobes. A larger percentage of those in bottom-sediments are anaerobes, the percentage increasing with core-depth.

Chitin-digesting bacteria have been found to be quite widely distributed in sea-water and bottom-deposits. They were found in abundance in the digestive organs of squid, thereby indicating that they may aid marine animals in the digestion of the resistant chitin which constitute the exoskeletons of most crustacea. Lipoclastic bacteria which liberate higher fatty acids from lipins and utilize the glycerol have been demonstrated in marine materials. These, together with those which create extremely reducing conditions, may account for the formation of long-chain hydrocarbons found in petroleum.

Mrs. C. B. Feltham has continued the experiments on the bacterial nutrition of marine organisms. Mussels have thrived for 14 months in the dark on a diet consisting exclusively of bacteria. George C. Ford has shown that sipunculid worms ingest and digest bacteria.

In collaboration with W. W. Smith, it has been shown that the halophilic bacteria found in Great Salt Lake, which is about eight times as saline as the ocean, are quite unlike marine species. The periphytic habits and physiological activities of the Lake bacteria indicate that they may cause certain types of carbonate precipitation.

Phytoplankton--W. E. Allen has devoted most of his time to statistical treatment of collections of phytoplankton. The microscope work on material obtained from inshore stations, begun in 1919, has been finished to January, 1935, and part of it has been finished to May, 1936. The primary computations and tabulation of data obtained from this material have been made to almost the same dates.

Several hundred catches of phytoplankton from the Gulf of California have been studied--one series collected by the Templeton Crocker Expedition of November, 1935, and another series collected by the expedition of Captain G. Allan Hancock in February to March, 1936. For these the data have been analyzed and reports have been written which are now in press. The report on phytoplankton collected by R. H. Fleming in the Gulf of Panama during the survey by U.S.S. Hannibal in 1933 has been completed.

Daily catches of phytoplankton have been continued at the pier stations of the Scripps Institution and Pt. Hueneme (more than 100 miles farther north).

Occasional trips to the United States Destroyer Base have been made to observe conditions of "fouling" on ship-bottoms and to discuss problems of fouling with officers of the United States Navy. Final corrections on the report on nine years of experimental researches on "fouling organisms" conducted at the Scripps Institution pier, prepared jointly by Professor W. R. Coe of Yale and W. E. Allen, have been made and the report is now in press.

Easter E. Cupp has analyzed for their nannoplankton content six series of hauls from the surface of the ocean to depths varying from 150 to 1000 meters taken on the Scripps from August, 1935, through September, 1936. The centrifuge-method used by H. H. Gran was followed. Records of species, and of abundance and distribution of Diatoms, Dinoflagellates, Coccolithophores, Silicoflagellates, small green Flagellates, Tintinnids, and other Ciliates were kept. Direct comparisons of nannoplankton with chemical and physical conditions were possible in most cases. Records of temperature and salinity are available for all six series, and oxygen, pH, and PO_4 for four series. Since the completion of work on nannoplankton samples, the greater part of her time has been spent in preparing a taxonomic paper on plankton Diatoms of the Southern California Region. Numerous sketches showing variations in the species have been made. Variations in species characters, seasonal distribution, and abundance are being considered.

A paper on "Low concentrations of deuterium oxide and the growth of marine diatoms" (E. E. Cupp, D. L. Fox, and G. F. McEwen) was published in the June, 1936, number of the Proceedings of the Society for Experimental Biology and Medicine.

Foraminifera--Prior to his retirement on August 31, 1936, Dr. T. W. Vaughan, in cooperation with U. S. Armstrong, completed a comprehensive report on fossil foraminifera from Trinidad.

Zooplankton--Martin W. Johnson has continued a study of the seasonal production and distribution of zooplankton off the California Coast. A special cruise for the collection of zooplankton, water-samples, and bottom-deposits was made off Cape Mendocino aboard the United States Coast and Geodetic Survey Guide during July, 1936. Biweekly collections are now being made at the Scripps Institution pier for the study of inshore production of copepods.

A report on the production and distribution of zooplankton in the Bering Sea and Bering Strait, based on collections made at 100 stations by the United States Coast Guard Chelan, has been completed and presented for publication.

A description of two new species of deep-sea copepods from the North Pacific has been published (Bull. Scripps Inst. Oceanog. Tech. Ser., v. 4, No. 2, 1936), and a manuscript describing the final metamorphosis of the male Aegisthus mucronatus, a deep-sea copepod, has been presented for publication.

The life-histories of several copepods are being investigated and it has been possible to work out completely all of the developmental stages of one of the most important offshore Pacific species, namely, Eucalanus elongatus var. bungii (Trans. Amer. Micros. Soc., v. 55, No. 1, 1937). The study of the taxonomic status and distribution and reproduction of the Pacific varieties of Eucalanus elongatus has been continued and a preliminary report is ready for publication.

C. R. Monk is engaged in a systematic and distributional survey of the Harpacticid copepods of the Pacific Coast. Experimental work on the breeding and migratory habits of Limnoria lignorum, the wood gribble, is in progress.

Biology of fishes--F. B. Sumner and P. Doudoroff have extracted and measured the amount of melanin from series of fishes which had been subjected to different conditions of optical stimulation, both as regards background and incident light. The amount of melanin extracted from a given lot of fishes was found to bear an inverse relation to the albedo of the background, probably varying inversely as the logarithm of the albedo. Intensity of incident light also played a part in determining the production (or loss) of melanin, higher illumination favoring pigment production (or retention). Under the degrees of illumination employed by them, however, the influence of this factor was small in comparison with that of the albedo of the background.

An extended series of experiments has been commenced with a view to discovering some of the physiological differences between fishes which have been acclimatized to widely different temperatures. Past experiments in this laboratory have shown that the rate of respiratory metabolism is one of the chief factors concerned, but these previous experiments have scarcely passed the preliminary stage.

P. Doudoroff has spent many months in devising and constructing an apparatus for the study of the reactions of fishes to gradients in the water. Experiments with temperature-gradients have already been commenced and have yielded some interesting results. It is planned that other gradients in the water, physical and chemical, be employed, and that the reactions of various fishes be studied in relation to species and to the past history of the individuals.

Percy S. Barnhart's book on "Marine fishes of Southern California" has been published by the University of California Press.

Physiology--Culminating research which was carried on at intervals over a period of some four years, a paper was published on "The habitat and food of the California sea mussel" as a bulletin of the Scripps Institution. This paper, edited by D. L. Fox, deals with the survival period of mussels in sea-water of various concentrations both hypotonic and hypertonic, types of food, feeding mechanisms, rate of digestion, digestive enzymes of the animal, and related subjects. Collaborators in the paper are D. L. Fox, G. W. Marks, F. O. Austin, and Horace M. Buley.

Further work on the mussel has been made possible by assistance from the Works Progress Administration. During the current year D. L. Fox has been able to resume experiments dealing with the biochemical effects of both hypotonic and hypertonic solutions of sea-water upon the tissues of the animals. R. T. Young collaborated in this work by making parallel histological studies. Another problem concerns calcium metabolism and the manner in which the mussel may accumulate calcium from the sea for its metabolic processes and shell building. A study was made of the quantity of water which mussels may pump per day through their gill chambers. It was established that the mussel filters water completely of suspended water, propelling it through the gill chamber at an average rate of about 2.5 liters per hour.

Continuing work on the biological effects of deuterium, made possible by a grant-in-aid from the National Research Council for the year 1934-35, D. L. Fox, with the collaboration of E. E. Cupp and G. F. McEwen, studied the effects of low concentrations of the heavy-water isotope upon two pure, isolated strains of marine diatoms, Nitzschia bilobata and N. closterium.

One of the chief lines of research at present and during the past several years is the investigation of various carotenoid pigments in marine materials and in marine animals, with special reference to nutrition.

Marine sediments--Since the retirement of Dr. T. Wayland Vaughan and the departure on leave of absence of Roger Revelle last August, R. H. Fleming has been in charge of the study of sediments. The work has been done by two skilled workers furnished by the Works Progress Administration and by part-time assistance of several unskilled workers. The program has been a continuation of that undertaken last year, namely, a systematic study of the large number of sediment-samples from the Pacific which are stored at the Institution. All samples have been catalogued and filed. For all those samples for which the amount was sufficient, portions have been removed, air-dried, and ground. These portions were then turned over to the chemical laboratory, where they were analyzed for their organic nitrogen-content. These nitrogen-analyses have been completed on all samples available at the Institution. The following projects are now under way: (1) The determination of the moisture-content of all samples analyzed for nitrogen-content; (2) the determination of the amount of occluded sea-salt by means of titration of the chloride leached from a known amount of the sample; (3) mechanical analysis of sediment-samples collected by the Scripps off the Southern California Region and by the Hannibal off Central America. To date, 95 mechanical analyses have been completed.

During recent years, most of the sediment-samples collected by the Scripps have been taken with a coring tube. The cores obtained have been from 10 to 60 cm long. These cores have been separated into a "surface"-portion and into segments about seven cm long. Each of these segments is being handled separately so that considerable information is being gained on the vertical differences in the composition of these sediments in the upper 50 cm.

The Section has cooperated with M. L. Natland in supplying him with samples for the study of the distribution and ecology of the foraminifera and, in return, has received about 50 samples collected by him off the Southern California Coast.

A series of 45 composite beach-sand samples collected by E. C. LaFond between the Canadian and Mexican borders have been mechanically analyzed.

Samples accumulated during the year consist of those from Natland and LaFond, 55 cores and 30 snapper-samples collected by the Scripps, 36 samples collected by the Hannibal in the Caribbean, 23 collected by the United States Coast and Geodetic Survey Guide, and 40 from the United States Coast and Geodetic Survey Pioneer.

Miscellaneous activities--Papers have been presented at the meeting of the American Association for the Advancement of Science in Seattle in June, 1936, at the meeting of the International Union of Geodesy and Geophysics in Edinburgh in September, 1936, where the Institution was represented by Dr. T. Wayland Vaughan and Dr. Roger Revelle, and at scientific meetings in Southern California.

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CURRENT-MEASUREMENTS IN THE GEORGES BANK CANYONS

H. C. Stetson

(Contribution No. 143 of the Woods Hole Oceanographic Institution)

Among the many speculations concerning the origin of submarine canyons, bottom-currents of various types have been appealed to frequently. This is one theory to which it is possible to apply some quantitative data, and to form an estimate as to the importance which may be attached to this means of producing submarine canyons, both now and in past ages. I refer of course to normal currents due to differences in densities caused by temperature and salinity, and to those which have a tidal origin, and not to the type recently proposed by Daly. Consequently during the summer of 1936 measurements of the bottom-currents were made in three of the submarine canyons of Georges Bank from the research vessel Atlantis of the Woods Hole Oceanographic Institution. Because of the physical difficulties of obtaining readings on the bottom in deep water, in a region where tidal currents at the surface are strong, the results are far from giving a complete picture. Nevertheless, some idea may be obtained of the magnitude of the velocities which might be expected.

The instrument used was an Ekman meter which is too well known to warrant detailed description here. For an account of its construction, one should refer to V. W. Ekman's publication (An improved type of current-meter, Conseil Perm. Internat. J. Conseil, v. 7, pp. 3-10, 1932). Velocities are measured by recording the turns of a delicately balanced propeller, and a device controlled by a compass-needle gives the direction of the current. The instrument is designed to be suspended from a wire, and when it has been lowered to the desired depth the propeller is released by means of a messenger which is slid down the wire. It is stopped in the same manner by another. Consequently, only the current at a given level is recorded and the machine does not register during lowering or raising. Due to the motion of the ship and the inevitable wire-angle, it is impossible to get readings close to the bottom in deep water by the usual procedure of lowering the meter on a wire. The instrument, therefore, was suspended in a framework of brass pipe fitted with a device for releasing one messenger when the frame touched the bottom, and another when it was hoisted up again. While on the bottom, the frame was buoyed because at the depth at which the work was carried on it is practically impossible on an anchored station to keep the ship from swinging excessively. Using a frame set on the bottom has an additional advantage, in that it eliminates the necessity of making a correction for the surge of the ship.

The frame was constructed of 3/4-inch brass pipe with standard fittings. All the other parts were also of brass. There is nothing significant in the dimension of parts or materials used. The bows are fastened at the top by U-bolts to a plate which has a hole in the center to admit the tripping ring. The device for releasing the first messenger was adapted from one constructed by Fridtjof Nansen (Methods for measuring direction and velocity of currents in the sea, Conseil Perm. Internat. Pub. de. circonstance, No. 40, 1906, Pl. II, Fig. 3). The apparatus is operated in the following manner. The line from the surface ends with a ball-bearing swivel to which is shackled a two-part wire-bridle. The longer part is permanently made fast to a U-bolt set in the head-plate, and the shorter part ends in an oval iron ring. This ring is passed through the hole in the center of the head-plate and engages the top hook of the trigger, which is then held in a horizontal position by the weight of the frame, which is now taken by this part of the bridle. The second messenger is controlled by a push rod which is free to move up and down in guides made of short sections of one-inch pipe, fastened to the under side of one of the legs of the frame. The push rod is just long enough to pass through the topmost guide, which is partly cut away on the under side in order to allow the end of the rod to engage the loop of the wire holding the second messenger. While the frame is being lowered, the push rod is held in place by a wire, which is made fast to the short part of the bridle just above the ring. As this part takes all the weight of the frame during the lowering, the push rod is thus held up and its end kept from slipping past the first guide, thus releasing the second messenger.

When the frame touches the bottom, the short part of the bridle goes slack, and the trigger--no longer held horizontal by the strain on the ring--falls, dropping the first messenger from the lower hook. Releasing the short part of the bridle also slacks the line holding the

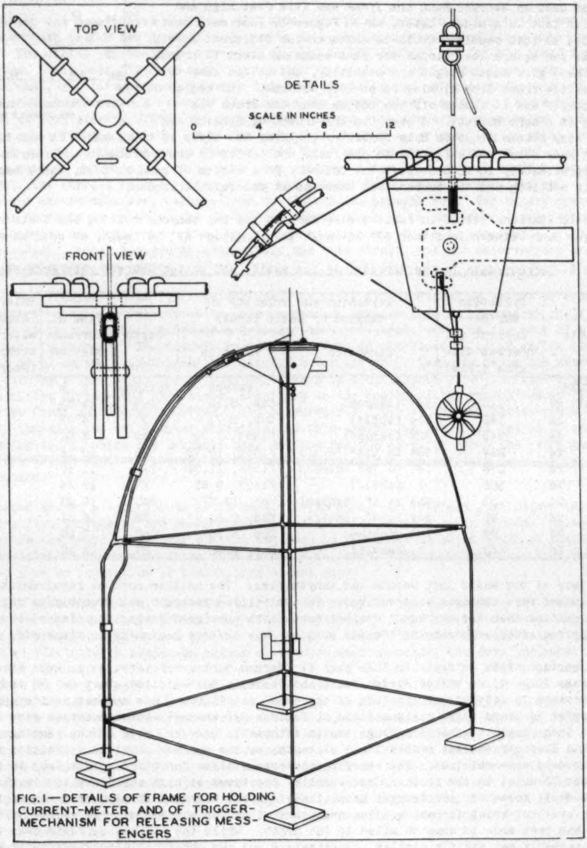

FIG. 1—DETAILS OF FRAME FOR HOLDING CURRENT-METER AND OF TRIGGER-MECHANISM FOR RELEASING MESSENGERS

push rod, which is now kept in place by its foot pressing against the bottom. The frame is hoisted by the long part of the bridle, and as it leaves the bottom the push rod drops down until its end, around which has been passed the loop in the wire holding the second messenger, clears the slot in the under side of the topmost guide--thereby allowing the second messenger to drop. Since it was possible by the feel of the line to tell when the frame touched bottom and when it was completely clear, the time-interval during which the meter was recording could be measured with reasonable accuracy. What slight errors there may have been in timing the arrival and departure were compensated for by allowing the machine to operate for at least 30 minutes.

When used on Georges Bank the frame was five feet high and about five feet on a side. Later, as in Figure 1, four more feet were added so that readings could be taken at two different levels. The frame had square lead blocks for feet weighing about 10 pounds each. These gave added weight and stability, and at the same time prevented the frame from sinking in on soft bottoms. The center of the propeller was 11 inches off the bottom when the frame was standing on a hard surface. A check on the amount of sinking was made on oozy bottom in Woods Hole Harbor by chalking the sides of the leads. It was found that the feet sank about three-fourths to one inch, and therefore the current in the canyons was measured approximately 10 inches above the bottom. On a bottom of sand or silt, there was no appreciable settling and the current was measured at the full 11 inches.

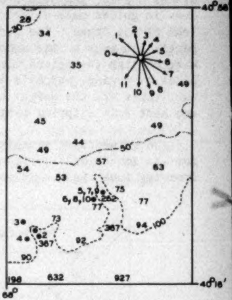

FIG. 2—POSITION OF CURRENT-STATIONS ON GEORGES BANK

The 10 stations listed in Table 1 were made in the two canyons cutting the southern margin of Georges Bank between longitude 67° 56' west and longitude 67° 38' west, as well as on the flat surface of the shelf just beyond the canyon-rims. The weather and the requirements of other work prevented more complete observations. The velocities recorded can probably be regarded as somewhat smaller than the average. Weather-conditions were good during the time of observations, and the spring-tides accompanying the new moon on July 18 were beginning to slack off.

Table 1--Current-data in the canyons, on the shelf, and at the nearest reference-stations

Station	Date	Direction surface-current at nearest diagram (true)	Direction and velocity in canyons or shelf (true)		Depth	Time at current-station	Interval after high or low water at reference station (Georges Shoal)
			Direction	Velocity			
	1936	°	°	cm/sec	fathoms	h m	h m
1	July 22	115	144 (canyon)	Ebb, 3.12	220	14 55	2 21
2	22	142	214 (shelf)	Ebb, 3.71	73	4 07	4 03
3	24	249	224 (canyon)	Flood, 1.75	230	8 52	1 11
4	24	294	154 to 214° (shelf)	Flood, 12.76	78	10 16	2 35
5	26	278	144 to 164°(canyon)	Flood, 11.08	210	11 10	1 55
6	26	328	? (shelf)	Flood, 5.65	77	12 38	3 23
7	26	33	354 to 4° (canyon)	Ebb, 10.37	260	15 07	5 52
8	26	65	344 to 3° (shelf)	Ebb, 2.31	73	16 24	0 51
9	26	98	154 (canyon)	Ebb, 5.55	260	17 29	1 56
10	26	133	? (shelf)	Ebb, 0.96	77	18 40	3 07

The surface tidal currents in this part of Georges Bank are rotary, as is well known, and the diagrams (Fig. 2) on United States Coast and Geodetic Survey pilot-chart No. 70 indicate little decrease in velocity at the turn of the tide. (In Figure 2 the numbers on the current-diagram refer to hours after maximum flood at Pollock Rip Channel, and the arrows give the direction; 1/8 inch equals 1 knot; soundings are in fathoms.) However, some of the readings were taken when the flood or ebb was running full strength, so the maximum possible velocities for those particular days were obtained. The nearest reference-station for tidal predictions is Georges Shoal--some 70 miles to the north. Consequently, the times of high and low water in the canyons will precede it somewhat, and Georges Shoal itself is one hour and 15 minutes ahead of its reference-station, which is Boston. The nearest station for which a diagram of the surface-currents has been made is some 30 miles to the north. While the surface-currents over the canyons are probably not exactly similar, nevertheless one can obtain an approximation of what is taking place. The directions given are all true.

On July 22, at 14^h 55^m, a station was made in the westerly of the two canyons near its head in 220 fathoms. A current of 3.12 cm/sec (about 0.061 knot) was found flowing 144° on the ebb. At the time the station was made, the ebb-tide must have been running about full strength. The surface-currents were running 115°. About one hour later another station was made on the flat surface of the shelf just beyond the edge of this same canyon in 73 fathoms. A current of 3.71 cm/sec was recorded flowing 214°. The surface-currents at this same time were flowing 142°.

Two days later the observations were repeated further down toward the mouth of the canyon. Near the peak of the flood the velocities recorded were 1.75 cm/sec for the canyon in 230 fathoms (0.034 knot) as against 12.76 cm/sec for the shelf (0.25 knot) in 78 fathoms. The current was flowing across the canyon 224° and in approximately the same direction on the shelf, 154° to 214°. At this time the surface-currents were flowing 294°. In this particular canyon the velocities recorded are less than for the nearby shelf.

On July 26 six consecutive stations were made alternately between valley-bottom and shelf in the easternmost of the two canyons. As nearly as possible, the same positions were occupied each time. The depths for the canyon ranged from 210 to 260 fathoms and for the shelf from 73 to 77 fathoms. The flood-tide had been running nearly two hours at Georges Shoal when the first station was made, and for a somewhat longer interval in the canyon as it lies farther offshore. A velocity of 11.08 cm/sec was recorded flowing up the canyon (144° to 164°). The surface-current was already flowing 278°. The next canyon-station was made after high water, but the current was still flowing inwards. A little more than an hour later this lag is still apparent on the shelf as the current there is flowing 344° to 3° and the surface-current 65°. When the next canyon-station was made, a little more than one hour later, the surface-current had only swung to 98°, the current in the valley-bottom was flowing 154°, which is straight out. Scanty and incomplete as the data are, nevertheless two points are brought out. The rotary system of the offshore currents is upset by the topography, which seems to be the controlling factor as far as the canyons are concerned. The flow is now in and out. There is apparently a lag, which is to be expected. Local topography undoubtedly has some effect, but the observations are too scattered to determine its amount.

Let us now consider these currents and their possible effectiveness as agents of erosion. Unlike the first case, the velocities in this canyon are greater than on the nearby shelf. Topographically it is a good deal narrower and longer than the first, and possibly more of a funnelling effect is exerted. The highest velocity recorded on the flood is 11.08 cm/sec (0.216 knot), with 10.37 cm/sec (0.203 knot) the strongest for the ebb. They are below the average as the neap-tides were just beginning on July 26. There is a difference of 40 per cent between the velocities of the spring- and neap-tides, according to the charts of the region issued by the United States Coast and Geodetic Survey. The measurements apply to the surface-currents. If we arbitrarily increase the two highest velocities by this amount, we get 15.51 and 14.52 cm/sec for the spring-tides, which are probably near maximum for the level at which the readings were taken. These values must, of course, be decreased somewhat for the currents actually in contact with the bottom.

As stated above, a velocity of 12.76 cm/sec (0.25 knot) was recorded just before the neap-tides on the flat surface of the shelf where no valley is at present being eroded. On August 8, the day before the neaps, a 13-hour station was made on the shelf 18 miles south of Block Island. At the same level, maximum velocities of 9 cm/sec were found. The soundings over this bottom are regular and give no indication of channelling of any kind.

It would seem, therefore, that the velocities recorded in the canyons are the normal ones which occur on the shelf under present-day tidal conditions. These currents, therefore, are merely flowing in preexisting cuts and are not the cause of them. It does not seem probable that they could be particularly competent agents of erosion when attacking the more indurated material which we know makes up part of the valley-walls. If this be the case in a region of strong tidal currents such as Georges Bank, they would be even less effective farther south where smaller velocities might be expected. Such velocities, however, as are found on Georges Bank would be sufficient to move the finer-grade sizes in an unconsolidated deposit. Hence once the cuts were made, these same currents might be very effective in keeping them open by preventing or checking deposition. On the basis of the above evidence, we are justified in eliminating from further consideration present-day bottom-currents as forces which are capable of forming the east-coast canyons. They may have helped to preserve them, but that is the full extent of the part which they have played. Nor does it seem likely that the type of currents which we have been discussing behaved in the past very differently from the way that they are doing today.

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SHORT-PERIOD VARIATIONS OF OCEANOGRAPHIC CHARACTERISTICS IN THE WESTERN NORTH ATLANTIC

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The existence of short-period variations of oceanographic characteristics at fixed levels in the oceanic basins has been demonstrated by various investigators (Bjørn Helland-Hansen and Fridtjof Nansen, The eastern North Atlantic, Geofysiske Publikasjoner, v. 4, No. 2, 1926, 71 pages; Bjørn Helland-Hansen, Report of the scientific results of the *Michael Sars* North Atlantic deep-sea expedition 1910--Physical oceanography and meteorology, Part 1 (text), 1930, 115 pages; Albert Defant, Die Gezeiten und inneren Gezeitenwellen des Atlantischen Ozeans, Wiss. Ergeb. Deutschen Atlant. Exped. *Meteor* 1925-1927, v. 7, Part 1, 1932, 318 pages). But since such information is scanty, a study of the question in the western North Atlantic was begun with the establishment of Station 2639 (66° 25' west, 35° 07' north) by the *Atlantis* July 9 to 13, 1936. (For details of the operation of this Station and complete discussion of the results, see H. R. Seiwell, Short-period vertical oscillations in the western basin of the North Atlantic, Papers Phys. Oceanogr. and Met., v. 5, No. 2, in press.)

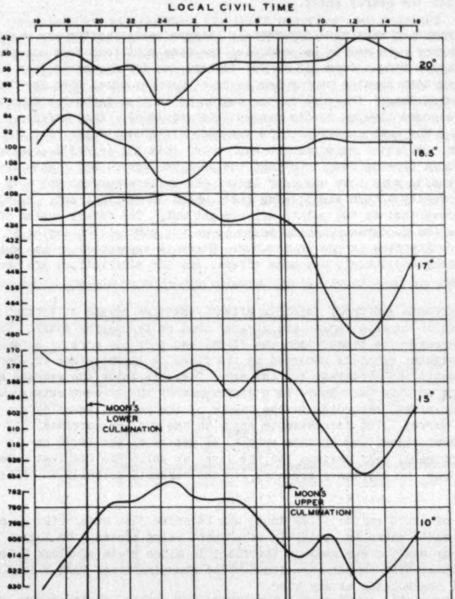

FIG. 1—TIME-DEPTH VARIATION OF 20°-, 18°.5-, 17°-, 15°-, AND 10°-ISOTHERMS, *ATLANTIS* STATION 2639, 24-HOUR PERIOD BEGINNING $15^h 30^m$, JULY 12, 1936

The present discussion is confined chiefly to the results of a series of approximate two-hour samplings of the upper 1200 meters of the water-column at Station 2639 during the 24-hour period beginning $15^h 34^m$, July 12, 1936. The observed vertical range of the isotherms for 20°, 18°.5, 17°, 10°, and 5° are given in Table 1 and their depth-time variations are illustrated in Figure 1, possible connections with the tidal wave being suggested by the appearance of approximate 12- and 24-hour periods.

Vertical variations of isotherms (and other characteristics in the sea) may be produced either by horizontal or vertical shifts of the water-mass. However, a detailed study of the horizontal gradients of the 17° and 10° isotherms in the vicinity of Station 2639 revealed that the minimum horizontal velocities (at the respective mean depths of these isotherms) required to produce the observed vertical displacements of isotherms would need to be in excess of 100 to 200 cm per second; such values are considered outside the realm of probability. Hence, it seemed reasonable to conclude that the observed variations of temperature and other oceanographic characteristics at Station 2639 resulted primarily from vertical oscillations of the water-column rather than from horizontal displacement of the water-layers.

Table 1

Isotherm	Mean depth	Total depth-range
	meters	meters
20.0	60	42 - 76
18.5	101	83 - 118
17.0	428	408 - 482
15.0	591	571 - 633
10.0	816	777 - 830
5.0	1265	1242 - 1285

Harmonic analysis of depth-variations of the 20°, 17°, and 10° isotherms (for the 24-hour period beginning $15^{h}\ 34^{m}$, July 12) gave the following results:

$$H_{20^\circ} = 55.4 + 7.4 \cos (2\pi/24)(t - 5^{h}.2) + 1.8 \cos (2\pi/12)(t - 5^{h}.8) + 5.6 \cos (2\pi/8)(t - 5^{h}.2)$$

$$H_{17^\circ} = 430.4 + 27.5 \cos (2\pi/24)(t - 16^{h}.6) + 14.0 \cos (2\pi/12)(t - 5^{h}.2) + 9.4 \cos (2\pi/8)(t - 0^{h}.9)$$

$$H_{10^\circ} = 802.4 + 24.7 \cos (2\pi/24)(t - 17^{h}.4) + 4.1 \cos (2\pi/12)(t + 1^{h}.6) + 2.3 \cos (2\pi/8)(t - 6^{h}.4)$$

where t stands for the number of lunar hours after the moon's lower culmination on July 12.

Good convergence is obtained between values calculated by means of the above equations and the observational data; the close agreement of calculated and observed extreme positions for the 20°, 17°, and 10° isotherms during the 24-hour period beginning $15^{h}\ 34^{m}$, July 12, is illustrated by Table 2.

Table 2--Comparison of calculated and observed extreme isotherm-positions
(Figures in parentheses represent the approximate number of lunar hours after the lower culmination of the moon on July 12, 1936)

Isotherm	Calculated range	Maximum displacement	Observed range	Maximum displacement	Average deviation all values
°	meters	meters	meters	meters	meters
20	44.1 (17^{h}) - 70.0 (5^{h})	25.9	42 (17^{h}) - 76 (5^{h})	34	2.2
17	407.5 (4^{h}) - 481.1 (10^{h})	73.6	408 (5^{h}) - 482 (17^{h})	74	1.9
10	774.7 (4^{h}) - 822.3 (16^{h})	47.6	777 (5^{h}) - 830 (17^{h})	53	5.3

Considering the depth-variations of the isotherms examined (as shown by the previous equations), the effect of the 24-lunar-hour wave was most pronounced, its amplitude attained significant proportions in the principal thermocline layer (24.7 to 27.5 meters), and its phase increased with increasing depth. The 12-lunar-hour wave was less effective, and had an amplitude of 20 to 50 per cent of that of the 24-lunar-hour wave (4 to 14 meters in the thermocline). The 8-lunar-hour wave showed its greatest relative significance at the depth of the 20° isotherm where its amplitude (5.6 meters) was more than three times that of the 12-lunar-hour wave (1.81 meters), but reached its maximum amplitude (9.4 meters) at the depth of the 17° isotherm where it was relatively less important. It may be concluded tentatively that the 24-lunar-hour and 12-lunar-hour waves are connected with the diurnal and semidiurnal tidal waves, but no tidal significance, as far as is known, can be attached to an 8-lunar-hour wave.

The question now naturally arises as to the effect of vertical oscillations of the water-column on the significance of conclusions derived from the usual oceanographic investigations (for example, from a study of temperature-, salinity-, and oxygen-distribution at fixed levels in the sea). The present study is not based on sufficient data to warrant the use of the results to approximate the effect of vertical oscillations at Station 2639 beyond the time of observation, but it is possible from the standpoint of practical oceanography to ascertain the order of magnitude of variations which, in general, may be expected to take place at fixed levels in the sea, from which can further be demonstrated the degree of disparity to be expected in various oceanographic calculations on account of the existence of vertical oscillations.

Thus, considering the temperature-variations, the calculation of the values ($t^\circ_{max} - t^\circ_{min}$) for a series of fixed levels between the surface and 5000 meters (based on data obtained during the entire observational period of 4 1/4 days at Station 2639) gave the following results: At the surface the maximum temperature-difference was 0°.30; but at 50 meters, which laid in the summer thermocline, it had increased to 2°.66; and below, in the relatively homogeneous water, between 200 and 400 meters, variations of only 0°.31 to 0°.36 were obtained. On entering the principal thermocline, which approximately laid between 400 and 1200 meters, the variations in ($t^\circ_{max} - t^\circ_{min}$) again became great, increasing from 0°.90 at depth 500 meters to a maximum value of 1°.42 at depth 800 meters and then falling off continuously to 0°.79 at depth 1100 meters and to 0°.50 at depth 1200 meters. In still deeper water, below the thermocline, values of ($t^\circ_{max} - t^\circ_{min}$) continued to decrease with decreasing vertical temperature-gradient; between 1400 and 2000 meters the values declined from 0°.36 to 0°.09 and continued to diminish still deeper until at depth 5000 meters the value of ($t^\circ_{max} - t^\circ_{min}$) was 0°.02--the approximate error of the thermometers.

A similar variation was observed in the case of oxygen. Values of ($O_{2\,max} - O_{2\,min}$) greater than 0.15 cc per liter occurred in the upper 2250 meters--with maximum values, 0.30 to 0.60 cc per liter, coinciding with the maximum vertical oxygen-gradient, between 50 and 200 meters. For still deeper water the value of $(O_{2_{max}} - O_{2_{min}})$ decreased, coinciding with the decreased oxygen-gradient, but this value was never less than 0.07 cc per liter for any particular fixed level.

The short-period variations of oceanographic characteristics at fixed levels may cause significant discrepancies in calculations of the dynamic topography, current-velocities, water-transports, and similar results in the sea. Thus, two calculations of the anomaly of dynamic height based on two separate samplings of the water-column at Station 2639 (series C, 22^h 27^m, July 9, to 2^h 00^m, July 10; series H, 13^h 35^m to 17^h 18^m, July 11, LMT) showed a discrepancy, with reference to 2000 meters, of 8.45 dynamic centimeters; this is sufficient (at the latitude of Station 2639) to produce an error of 25.3 cm per second in the calculated horizontal current-velocities normal to two verticals in the sea separated by a distance of 40 km.

A numerical example of the effect of vertical oscillations at Station Atlantis 2639 on calculations of the transport of water between two verticals in the sea may be obtained by comparing the transport as calculated between series C of Station 2639 and Station 1226 by the Atlantis (35° 07' north, 71° 53' west) with the value obtained from a similar calculation between series H of Station 2639 and Station 1226 (these total transport-calculations were carried out by the method of W. Werenskiold; see Coastal currents, Geofysiske Publikasjoner, v. 10, No. 13, 1935, 14 pages). Thus, the following results of the two transport-calculations between surface and a 2000-meter reference-level were obtained:

Total transport calculated between series C of Station 2639 and Station 1226 . . .	64×10^{11} cm^3 per second
Total transport calculated between series H of Station 2639 and Station 1226 . . .	19×10^{11} cm^3 per second

These results, which illustrate the order of magnitude of the disparity which may arise in a calculation of the total transport of water between two verticals in the sea on account of vertical oscillations of the water-column, are somewhat startling in view of the fact that under the usual methods of oceanographic sampling either series C or H might have been considered representative of Station 2639. The percental difference amounts to $(64 \times 10^{11} - 19 \times 10^{11})/(64 \times 10^{11}) = 70.3$ per cent.

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THE NEW PLANS FOR THE COOPERATIVE INVESTIGATION OF THE NORTH ATLANTIC'S CIRCULATION

Columbus Iselin

The ocean is so huge that it is most necessary for the relatively few men in the world who are actively engaged in studying its circulatory movements to combine forces in order to secure more adequate observations. Nevertheless until recently it has proved most difficult to promote any scheme whereby a number of vessels from different nations could work simultaneously on a given problem. Therefore, it is most encouraging that during the last year two ambitious cooperative undertakings have progressed well beyond the stage of wistful planning.

Each of these projects seeks to solve a definite and important problem in oceanic circulation that would be difficult and impractical for any one nation or institution to attack alone. The first of these plans was put forward by Professor Bjørn Helland-Hansen, and he now is the Chairman of a committee of the International Union of Geodesy and Geophysics which has been appointed to work out the details. It is proposed that during the early summer of 1938 as many research vessels as possible, each carrying a crew of well-trained scientists and technicians, should collect modern hydrological and meteorological data from a relatively small area of the so-called North Atlantic Current, namely, just east of where the Gulf Stream appears to branch and to begin to dissipate part of its energy in eddies. In other words, as close a network of stations as possible will be made in mid-ocean across the latitudes of easterly current. It is expected that at least six vessels will be able to take part during a seven-week period. The great mass of subsurface temperature- and salinity-data thereby collected will go a long way towards solving the important question of how complex the pattern of oceanic circulation really is. We do not know, for example, whether or not our analysis of existing data even approximates the true current-pattern. It may be that it is permissible to interpret subsurface observations collected over a period of years as if they were made simultaneously, and it may be that a relatively wide network of stations is sufficient to show the major features of oceanic circulation, but these vital questions can only be definitely answered if at least on one occasion a mass of data is secured from a restricted area during a short period of time. The area in mid-ocean east of the Grand Banks was selected, not only because it is an important one where the currents are probably relatively complex, but also because it is a convenient meeting place for vessels from this country and from Europe. Moreover, from the meteorological standpoint this region is of equal interest. It is proposed that during the course of the hydrological work each vessel will carry out detailed meteorological observations that can be studied in the light of a very complete set of weather-maps that will at the same time be constructed with the aid of observations from all passing commercial vessels. It is expected that during the period of work the development of at least one storm will be followed in more detail than has ever before been possible over the ocean. Let us hope that no unforeseen event will interfere with the carrying through of this work as soon as possible.

The second cooperative investigation, although it involves fewer vessels, and therefore less money, will extend over a considerable period of years and will, I think, produce equally fundamental results. This plan, which has progressed to the point where work is about to start (June, 1937), is largely the result of the efforts of a committee of the Royal Society of London. These men recognized that the facilities of the Bermuda Biological Station, because of lack of funds, were not being fully utilized. They also recognized that variations in the rate of circulation of the North Atlantic undoubtedly had an important bearing on fluctuations of the British fisheries and climate. A generous grant of money was therefore secured from the British Government. This will provide a small vessel to be operated from Bermuda and also the necessary personnel and equipment to supplement that already available there. This committee also enlisted the willing aid of the Woods Hole Oceanographic Institution. Thus at least three agencies will be cooperating in this study over a five-year period. The plan of investigation has been worked out in considerable detail, but it will be sufficient here to state only the broad aspects of what should prove a most fruitful cooperative effort.

Using the Atlantis and the new Bermudian boat, the variations in transport of the Gulf Stream will be followed until it can be shown whether or not they are sufficient to account for the very considerable changes met with on the fishing grounds on both sides of the Atlantic. The volume of the Gulf Stream is of course only one manifestation of the great North Atlantic Eddy. Thus in following the changes in the Gulf Stream's flow, a good idea will be obtained of the variations in intensity of the horizontal circulation of the ocean as a whole. It is not known, for example, whether currents are only subject to short-period and random fluctuations or whether on the whole they build up in intensity during a considerable period of years. Obviously varying amounts of energy are put into the currents by the winds and other climatic factors. It is hoped that the chain of events leading up to an increase in such a current as the Gulf Stream can be traced and also the results of such a change from the fisheries standpoint and from that of the climate of northwestern Europe.

While this may seem too ambitious a project, in the course of the work many less spectacular problems will have to be solved and, even if the main objective is not achieved, the more detailed results will easily justify the effort. For example, from the standpoint of northern Europe the variations in temperature and salinity of the coastal waters may easily be more closely connected with variations in the local wind than with changes in the major currents. Thus in trying to estimate the relative importance of these two factors it will be necessary to study intensively the effect of the wind on the surface-layer. For such work, Bermuda is almost an ideal base, for the permanent currents are probably slight and most of the surface-movement must result from the local wind.

The immediate and most gratifying results of the British grant are that it will enable the Bermuda Biological Station to expand its field of activities and additional men will have the opportunity to work on some of the important problems of oceanic circulation.

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PRELIMINARY REPORT ON THE NORTH ATLANTIC DEEP-SEA CORES TAKEN BY THE GEOPHYSICAL LABORATORY, CARNEGIE INSTITUTION

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(Published with the approval of the Director, U. S. Geological Survey)

A series of 11 cores from the North Atlantic sea-bottom between the Newfoundland Banks and the banks off the Irish Coast have been studied by a group of geologists of the United States Geological Survey. These cores were taken by Dr. C. S. Piggot of the Carnegie Institution's Geophysical Laboratory from the cable ship Lord Kelvin with the explosive type of sounding-apparatus, which he designed (C. S. Piggot, Apparatus to secure core-samples from the ocean-bottom, Bull. Geol. Soc. Amer., v. 47, pp. 675-684, 1936). This preliminary report is based largely on the results obtained by M. N. Bramlette, who studied the lithology, and Jos. A. Cushman, who studied the foraminifera.

The geographic position, the depth of water at each station, and the length of core obtained are given in Table 1.

Table 1--Geographic position, depth of water, and lengths of cores taken from North Atlantic sea-bottom

Station and core No.	Latitude north	Longitude west	Depth of water	Length of cores
	° ' "	° ' "	fathoms	meters
3	46 03 00	43 23 00	2575	2.82
4	48 29 00	35 54 30	2165	2.72
5	48 38 00	36 01 00	2640	2.82
6	49 03 30	32 44 30	2260	2.93
7	49 32 00	29 21 00	1780	2.62
8	49 36 00	28 54 00	700	1.24
9	49 40 00	28 29 00	2050	2.77
10	49 45 00	23 30 30	2295	2.97
11	48 38 00	17 09 00	2640	0.34
12	49 37 00	13 34 00	1770	2.43
13	49 38 00	13 28 00	1070	2.22

Core No. 3 was taken just off the Newfoundland Banks in the blue-mud zone, but all the others were taken in parts of the ocean where the bottom is blanketed with Globigerina ooze. Core No. 8 was taken on the Mid-Atlantic Ridge and core No. 11 struck volcanic rock.

In about 20 representative samples from each core the percentages of calcium carbonate, clay and silt, sand, and coarse sand were determined. Also the relative abundance of foraminifera, coccoliths, and diatoms was estimated in these samples. Material between these guide-samples was examined microscopically, especially in certain critical zones.

Two zones in which acid volcanic ash (refractive index near 1.51) is common were found. The upper one was found in all the cores except No. 11, but the lower one has thus far been found only in the lower part of cores 4 to 7. Although in most of the cores the upper ash-zone is restricted to the upper part, in core No. 3 it is represented by scattered shards, but the core, despite its length, apparently did not reach that part of the ash-zone where the shards are most abundant. This upper ash-zone serves to correlate the cores and the lower ash-zone, where found west of the Mid-Atlantic Ridge, reinforces the correlation.

Besides the zones of volcanic ash, four other zones of distinctive lithology were found. These zones are characterized by a relative abundance of sand and pebbles, by a smaller percentage of calcium carbonate, and by a sparsity of organisms--foraminifera and coccoliths. They also have a distinctive texture. The pebbles are sub-rounded to angular and include a wide variety of rock-types--sandstone, gneiss, soft shale, and limestone--of which limestone is the most common. Some of the pebbles are as much as two cm across. These zones are interpreted as glacial marine-deposits formed during four separate glacial stages when continental glaciers were eroding the land. Drift-ice from the continental glaciers apparently transported considerable quantities of rock-debris far out into the oceanic basin. Larger boulders, some with facets and striae, have been dredged in latitudes as far south as the Azores, and have been interpreted as transported by Pleistocene ice-drift.

Glacial marine-deposits closely similar to these were described by E. Phillippi (Die Grundproben der deutschen Sudpolar-Expedition, Bd. 2, Heft 6, pp. 578-589, 1910) from the South Atlantic off the margin of the Antarctic shelf-ice. From that locality where they are now forming, Phillippi showed that they extended northward into the South Atlantic beneath a cover of first diatom ooze and, farther north, of Globigerina ooze.

In the equatorial part of the Atlantic, W. Schott (Die Sedimente des Aquatorialen Atlantischen Ozeans, Wiss. Ergeb. deutschen Atlantischen Expd. auf dem Forschungs-und Messungschiff Meteor 1925-1927, Bd. 3, part 3, pp. 120-130, 1935) interpreted an abrupt change from a surface-layer of warmer-water foraminiferal fauna to an underlying colder-water fauna as the boundary between post-glacial deposits and deposits of the last glacial epoch. In some cores he found below the deposits characterized by a colder-water fauna, other deposits containing a warmer-water fauna which he interpreted as inter-glacial.

Between the glacial marine-zones found in the North Atlantic cores the sediments consist chiefly of Globigerina ooze or limy clay much like that which is forming today in the same area.

The uppermost glacial zone is represented in all the cores but Nos. 3 and 11, and lies just below the upper volcanic ash-zone. Core No. 3, though nearly three meters long, did not reach the base of the upper ash-zone and so of course did not reach the top of even the highest glacial zone. Core No. 11 is evidently too short to have hit either the ash or the glacial marine-deposits. In cores 4 to 7 the glacial zones are relatively thin and are spaced at approximately equal intervals. Between the third and fourth glacial zones (in descending order) is the lower volcanic ash. Only the uppermost glacial zone has been identified east of the Mid-Atlantic Ridge. Other glacial marine-deposits are recognizable but their correlation is less certain.

Cores 3, 8, and 11 are markedly different from the others. Core No. 3 is distinctive for its uniformity in texture and composition. With the exception of three thin clay-layers that are widely spaced, this core consists of about equal amounts of clay and silt-sized clastic material,and clay and silt-sized calcium carbonate particles. Coccoliths are rather common throughout, but foraminifera are relatively rare.

In contrast, core No. 8 is characterized by an abundance of coarse sand and pebbles, by only the coarser volcanic glass shards which are not common, by abundant foraminifera, and by very little matrix of clay and silt sizes. According to our interpretation, currents move across this part of the Mid-Atlantic Ridge (Faraday Hills) with sufficient velocity to winnow out most of the fine-grained material and carry it into deeper basins such as that where core No. 9 was taken. Core No. 9 is characterized by a predominance of very fine-grained material.

Core No. 11 penetrated only about 15 cm of Globigerina ooze before encountering a deeply altered volcanic rock which it penetrated about 23 cm. Preliminary examination suggests that this rock may represent a submarine flow of basaltic rock.

It is evident from the large differences in depth below the oceanic floor to the top of the latest glacial marine-zone that the rate of deposition differs widely from place to place. In cores 4, 5, and 7, for example, the top of the latest glacial zone is about 30 cm below the top and, if the last glacial epoch is taken as 20,000 years ago, then the post-glacial deposition in these three cores was at the rate of approximately 20,000 years per foot. As core No. 3 did not reach the glacial zone, the rate of deposition there must have been something more than ten times as rapid. On the Mid-Atlantic Ridge the rate was somewhat slower and in some areas east of the Ridge the rate seems to have been several times as rapid as prevailed generally west of the Ridge.

C. O. Iselin (Recent work on the dynamic oceanography of the North Atlantic, Trans. Amer. Geophys. Union, 10th annual meeting, pp. 88-89, 1930), in studying some bottom-cores off the Irish Coast, concluded that the marked decrease in carbonate content below about 25 cm represented deposits of a glacial epoch. He estimated the rate of accumulation in that locality to be about one cm per 1000 years or 30,000 years per foot.

W. Schott (Op. cit., p. 129), after studying the short cores obtained on the Meteor Expedition in the equatorial Atlantic, estimated the average rate of accumulation by the depth to the top of the deposits formed during the last glacial epoch to be 25,000 years per foot. His estimates for various cores ranged from 14,000 to 57,000 years per foot.

The biologic evidence now available is Cushman's interpretation of the temperature-conditions revealed by the pelagic foraminifera at successive levels in the cores. He found that at some levels the foraminifera indicated warmer-water conditions than prevail in that part of the ocean today, whereas at other levels they indicated much colder-water than today. At other levels they indicated conditions nearly like those of today.

The physical evidence and the biologic evidence were purposely studied entirely independently. With but one exception, wherever the physical evidence indicated a glacial marine-zone the foraminifera indicated a cold-water environment. Likewise the interglacial zones were characterized by foraminifera that indicated conditions like today or somewhat warmer. The one exception is in core No. 9 where a cold-water fauna was found in a thin zone between the base of the upper ash-zone and the top of the latest glacial marine-zone--that is, a few cm above the top of the glacial zone.

In core No. 3, which apparently represents only post-glacial time, or part of it, the foraminifera indicate only slight departures from present-day conditions.

Below the lowest glacial marine-zone encountered in the cores the foraminifera indicate in each core conditions as warm as today or warmer.

From the evidence thus far available, we conclude that these long cores have penetrated sediments that represent not only all post-Pleistocene time, but some have penetrated also four glacial stages and three, or perhaps four, interglacial stages of the Pleistocene epoch. None of the foraminifera in the bottoms of the cores suggest Pliocene species.

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INVESTIGATION OF SUBMARINE TOPOGRAPHY DURING THE PAST YEAR

Francis P. Shepard

During the past year the United States Coast and Geodetic Survey charted several areas of considerable scientific importance. With the help of a grant received from the Geological Society of America and through the cooperation of the Survey, the writer was able to accompany the vessels during the most important parts of this work. The areas of special interest which were examined included the submarine canyon off the Hudson, the submarine trough southwest of the Mississippi Delta, and the great escarpment off Punta Gorda along the Northern California Coast.

Hudson Submarine Canyon

The submarine valley off the Hudson has been known to geologists since 1863 when it was described by Dana. It was not, however, till last summer that data became available to give us more than a very crude idea of this feature. It was formerly supposed that the shallow valley which extends across the shelf off New York Harbor connected with a canyon which extended down the slope beyond. The new survey shows that the two features are not actually connected but that the shallow valley dies out near the shelf-margin and the canyon heads about six miles to the northeast of the terminus of the valley. However, tracing the canyon down the slope it is shown to make a double bend and come into line with the inner valley for most of its length. This suggests the possibility that the two were formerly connected, but that they were separated as a result of a complex series of sea-level oscillations which allowed the filling in of the head of the canyon and the production of a new head as the result of a diversion of the inner valley.

The canyon off the Hudson is of tremendous proportions, having walls as much as 4000 feet high in some places. It has been traced out to depths of over 7000 feet without reaching its outer terminus. It cuts about 18 miles into the 100-fathom line, which is more than any of the other canyons off the east coast. On the other hand, Hudson Canyon is not different in general character from the canyons found all the way from Chesapeake Bay to Nova Scotia.

New canyons discovered--Carrying the surveys to the north and south of Hudson Canyon resulted in the discovery of five canyons previously unknown. None of these compares in magnitude with the Hudson although they would all compare favorably with the largest canyons on the slopes of the Appalachians. South of Hudson Canyon there is a gap of about 20 miles where no canyons exist although the survey in this area was not very complete.

Mississippi Submarine Trough

Last October a United States Coast and Geodetic Survey vessel made a careful investigation of the valley which lies southwest of the Mississippi Delta. It was found that this feature was quite different from the typical submarine canyons found off other coasts. Instead of the V-shaped base this valley has a broad flat floor which attains as much as ten miles in width. This width combined with steep walls makes the term "trough" applicable. However, the Mississippi Trough differs from such troughs as that of the Gulf of St. Lawrence in that it slopes outward continuously. Its outward gradient is approximately one per cent. The same gradient is found off the Passes of the Mississippi. Also the mud on the floor of this Trough is the same in character as that off the Mississippi Delta. This indicates that the floor of the Trough has been built up by Mississippi River deposition presumably in the Wisconsin glacial epoch when the sea-level was somewhat reduced. Probably the feature once had the same V-shaped profile that characterizes other submarine canyons.

Salt-domes--The steepness of the walls of the Trough were a source of surprise in view of the relation to the greater Mississippi Delta. However, it was found that where these walls were particularly steep they had dome-like projections associated with them. Other domes were found along the edge of the continental shelf and the dredging of one dome resulted in the discovery of rocky material. This proved to be a calcareous algal deposit. Examination of previous surveys showed that the domes could be traced from near the Delta westward along the shelf-margin to the point where the margin turns abruptly to the south.

These domes are in all probability salt-plugs like those found in abundance on the adjacent land-area. Their linear relation and their association with the shelf-margin leads to the belief that they were intruded along a fault-zone. This may also account for the fact that they have much more relief than any of the salt-domes on the continent. The possibility that they may be associated with rich oil-deposits is being considered by oil-companies. An interesting problem regarding international rights might arise in the case of the exploitation of these features.

Punta Gorda (San Andreas) Fault-Scarp

Off Punta Gorda, California, and in line of continuation with a curving fault-zone which has been traced north from Shelter Cove there is a large escarpment. This submarine cliff extends out almost at right-angles to the general trend of the California Coast. It causes an offset in the 1000-fathom curve of approximately 40 miles. The suggestion has been made that this scarp represents the great horizontal offset of the San Andreas Fault where this Fault crosses the continental escarpment. Last summer a portion of this escarpment and the adjacent sea-floor were surveyed. Notable discoveries in this work include the finding of gash-cracks or rifts on the narrow continental shelf inside the escarpment. These rifts are suggestive of recent horizontal movement along the great Fault. The absence of any vertical offsets along the shelf where it crosses the fault-line gave further indication of this horizontal movement.

The survey of the submerged scarp showed that it was free from valleys at least in the inner portion. This may indicate that the recency of the faulting has prevented valley-formation. It is observable, however, that other fault-scarps off the California Coast lack valleys also. The explanation is not yet clear regarding this point.

New bathymetric map off California

The writer can also report the completion of a series of new bathymetric maps extending all along the California Coast and covering the bottom out to 2000 fathoms. The maps are based on approximately a million of the new United States Coast and Geodetic Survey soundings. The sea-bottom is contoured at a 300-foot interval and the same interval is used for the adjacent lands.

These maps show what a remarkable topography exists off the coast. To the south there is a broad area comparable in general character to the topography of Southern California. Farther north a more normal shelf-and-slope topography is found, but with enormous submarine canyons cutting into it which can be traced outward to depths of 10,000 feet and more. Also great escarpments are found and mountains of volcanic aspect, some of the latter rising as much as 10,000 feet above their surroundings. The maps indicate the fertile field for geological study which awaits development.

Plans for publication

The material acquired in these investigations is to be published in full by the Geological

Society of America. The paper on the Mississippi Trough and the salt-domes should appear in the near future, as will also the new series of maps.

University of Illinois,
Urbana, Illinois

REPORT ON DYNAMIC STUDIES OFF THE CANADIAN PACIFIC COAST, 1936

John P. Tully

An investigation is being made of the oceanic currents off the Pacific Coast of Canada, with their tidal, seasonal, and annual variations, so that their effects on the fisheries may be determined in correlation with the current biological investigations.

Three studies are proceeding simultaneously, the first to observe continuously the meteorological factors that affect the sea, the second to prepare charts of the gradient-currents within 100 miles of the west coast of Vancouver Island, and the third to determine the distortion of the gradient-currents by the great tidal forces in this area.

A current-survey is tedious and costly, and in view of the cyclic nature of the variations in the physical conditions that cause movements in the sea, it is logical to first observe these cycles as cheaply and comprehensively as possible.

Daily observation of the sea-water temperature, salinity, and the atmospheric temperature, precipitation, wind-force, and wind-direction have been carried on at five stations since the inception of this program in 1934. From time to time observatories have been added, until at the present time there are 11 stations along the Pacific Coast of Canada engaged in this work.

The data are being smoothed by sevens and graphed as shown in Figure 1. Each day on these graphs represents the average of seven days, the three preceding and the three following the day marked. This artifice smooths the curves so that the daily variations do not overshadow the seasonal trends, and the small local variations disappear, but the true changes general in the area shown are not affected.

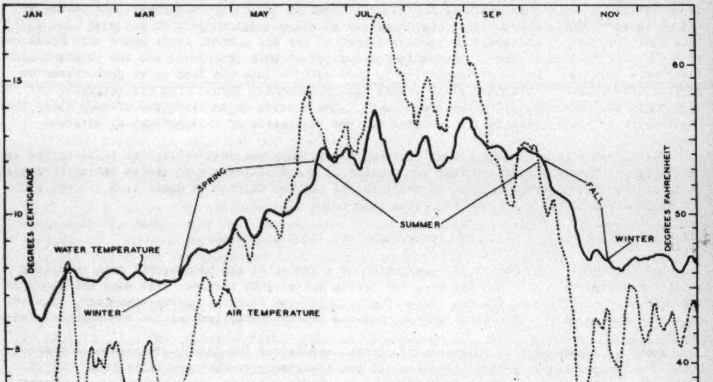

FIG. 1—QUATSINO STATION, WEST COAST VANCOUVER ISLAND, 1935

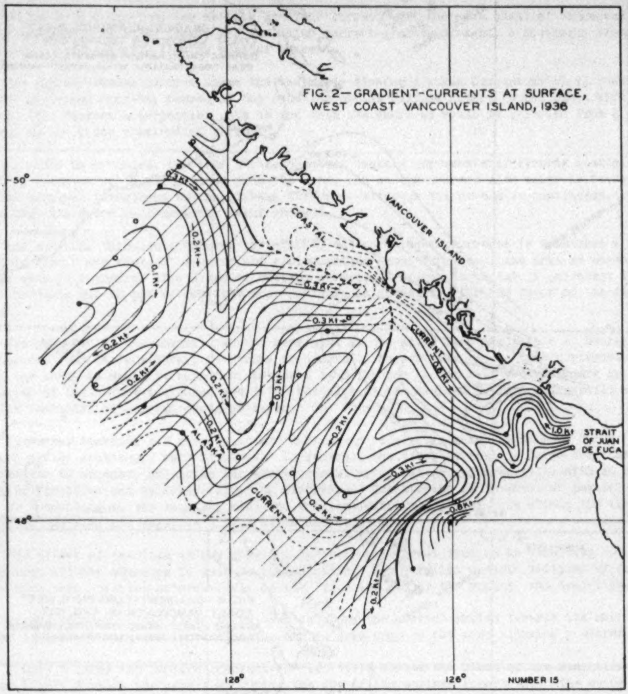

FIG. 2—GRADIENT-CURRENTS AT SURFACE, WEST COAST VANCOUVER ISLAND, 1936

From consideration of the cycles shown by these continuous observations it is possible to define summer as that period when the temperatures of air and water are at a relatively constant maximum, and the winter as that period when they are at a constant minimum. The spring and fall are periods of change from one stable season to the other.

In an oceanic current-survey, only those observations that are made during similar meteorological conditions can be correlated to make a chart. Since time is required for the progress of a survey, it is necessary to make all the correlated observations within a single period of meteorological stability, either in the summer or the winter. This allows the number of dynamic measurements to be reduced to a minimum and made to apply to the whole season instead of being applicable only to the time of observation.

The surface-conditions of the sea are largely affected by, and affect, the atmospheric weather. Correlations are being established between the temperatures of surface-water and air in the usual manner, and this is being carried a step further to show a relationship between regional precipitation and surface-salinity, which in turn may be used as a measure of land-drainage. The effect of this land-drainage on the coastal current-system may then be estimated by the continuous record of the direction and velocity of the wind, which serves as a key to the mechanical mixing of the surface-layers of the sea. In this way the marine and atmospheric meteorological observations serve to define the cycles that occur in the coastal currents, their limits and periodicity.

The three major current-factors in oceanic waters are wind, gradient, and tidal currents. The work of 1936 was concerned only with gradient and tidal currents.

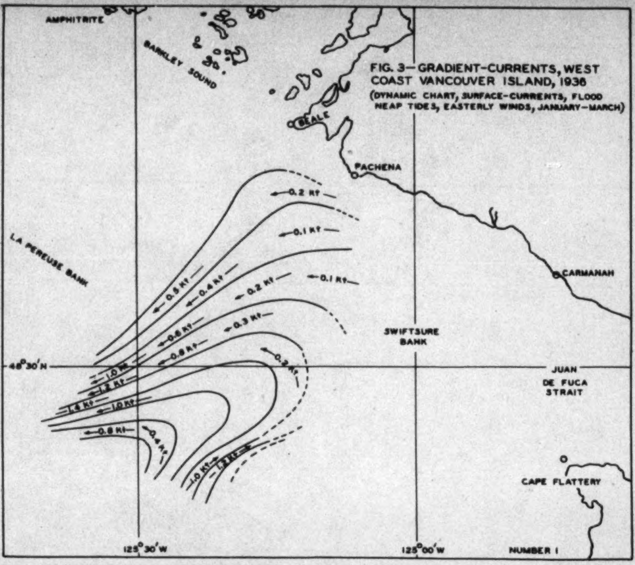

FIG. 3—GRADIENT-CURRENTS, WEST COAST VANCOUVER ISLAND, 1936
(DYNAMIC CHART, SURFACE-CURRENTS, FLOOD NEAP TIDES, EASTERLY WINDS, JANUARY—MARCH)

AMPHITRITE
BARKLEY SOUND
BEALE
PACHENA
CARMANAH
LA PEREUSE BANK
SWIFTSURE BANK
JUAN DE FUCA STRAIT
CAPE FLATTERY
48°30'N
125°30'W
125°00'W
NUMBER 1
0.2 Kt
0.1 Kt
0.1 Kt
0.5 Kt
0.4 Kt
0.2 Kt
0.6 Kt
0.3 Kt
0.8 Kt
0.2 Kt
1.0 Kt
1.2 Kt
1.4 Kt
1.0 Kt
0.8 Kt
0.4 Kt
1.0 Kt
1.2 Kt

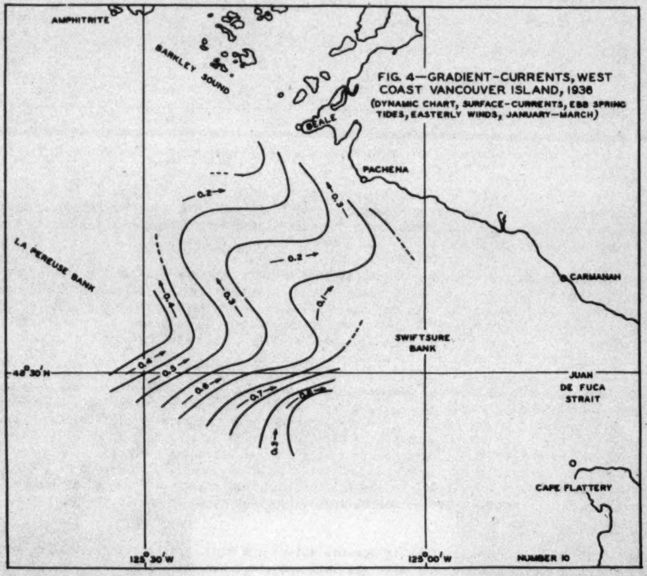

FIG. 4—GRADIENT-CURRENTS, WEST COAST VANCOUVER ISLAND, 1936
(DYNAMIC CHART, SURFACE-CURRENTS, EBB SPRING TIDES, EASTERLY WINDS, JANUARY—MARCH)

AMPHITRITE
BARKLEY SOUND
BEALE
PACHENA
CARMANAH
LA PEREUSE BANK
SWIFTSURE BANK
JUAN DE FUCA STRAIT
CAPE FLATTERY
48°30'N
125°30'W
125°00'W
NUMBER 10
0.2
0.3
0.2
0.4
0.3
0.1
0.4
0.5
0.6
0.7
0.8
0.5

Figure 2 is a chart of the surface gradient-currents off the west coast of Vancouver Island during the summer of 1936. There are two major current-systems present, a southerly flowing offshore and a northwesterly flowing coastal current.

The lightly-shaded portion shows the southerly flowing Alaskan Current which is a continuation of the Japan Current, caused by the rotation of the surface-waters of the whole North Pacific Ocean. This follows a serpentine path to and from the shore as would be expected from a consideration of the steep continental talus.

As would be expected, the land drainage-waters cause a northwesterly flowing coastal current to which fresh water is being added from the land, and on the seaward side water is being lost through marginal turbulence to the Alaskan Current. Although the stream is continuous, it appears that the water is constantly being changed.

The marginal turbulence between the coastal and the Alaskan currents is sometimes visible as "tide rips," and zones of sinking and rising waters occur throughout the area as shown by the dotted dynamic isobaths. The zones of maximum turbulence appear to be fairly permanent in position, probably due to the bottom-contours, but vary in intensity with the force of the two currents.

The behavior of the coastal current generated by the water from the Strait of Georgia draining through Juan de Fuca Strait is worthy of comment. Part of the water turns northwestward along the coast as would be expected, but part is deflected to the left and southward by the character of the bottom-contours, and joins the flow of the Alaskan Current while still maintaining its character of coastal drainage-water.

The tidal currents off this coast are definitely rotary, as shown by Marmer, being the resultant of two stationary wave-impulses. In general, the tidal current is large near the shore and smaller to seaward, and moves the whole coastal-water system differentially with an ever-changing direction and velocity, rotating clockwise. The current is in total or partial apposition or opposition to the existing wind and gradient-currents, giving rise within the tidal period to positive and negative acceleration and deflection.

The effect of the tide on the gradient-current pattern was studied by observing in detail a small area off the entrance to Juan de Fuca Straits. Two parallel dynamic sections of five stations each were observed consecutively on the flood and ebb of the spring- and neap-tides.

It was found that the flood-tides tend to crowd the current-system towards the shore causing an increase in the gradient-velocity, and to draw away on the ebb, allowing a decrease.

Figure 3 shows the surface gradient-current field during the flood of the neap-tides (chart 1) and Figure 4 shows the same area during the ebb of the springs (chart 10). The evident distortion of the flow is due to the difference of the relative magnitude of the tidal forces during the two ranges.

This program is being continued in an expanded form to determine the tidal-current cycles, and the wind and gradient-current fields during the summer and winter periods of meteorological stability.

Pacific Biological Station,
Nanaimo, British Columbia, Canada

OCEANOGRAPHY IN BRITISH COLUMBIA IN 1936

C. McLean Fraser

As in previous years, the work in oceanography in British Columbia during 1936 was largely centered in the activities of the Biological Board of Canada at the two main stations, Nanaimo and Prince Rupert, and at the several subsidiary field-stations, but several Government departments and various organizations gave valuable cooperation. Those making the greater contributions were: The Provincial Fisheries Department; the Provincial Game Commission; the University of British Columbia; the University of Washington (mainly through the Oceanographic Laboratories); the Canadian Pacific Steamship Service; the Naval Service; the Department of Health; the Department of Marine; the Hydrographic Service; the Meteorological Service; the Federal Department of Fisheries; and the National Research Council. Assistance from several individuals not connected with any of these organizations helped materially to add to the results obtained from the year's activities.

A large number of problems that may be considered minor problems, although they may be of much importance, take up much time and require much consideration each year, although each, in itself, may not be very time-consuming. Special reference cannot be given to such.

The nature of the larger problems, most of which are carried on from year to year, will be treated under the four heads: (1) Physical and chemical oceanography; (2) fundamental biology; (3) fisheries; (4) fisheries technology.

Physical and chemical oceanography--The work of charting the oceanic currents near the coast has progressed satisfactorily during the year. In the main, the hydrodynamic measurements were confined to the southern portion of the west coast of Vancouver Island.

During the year, four expeditions (three of them in this area) in H.M.C.S. Armentiers were made for the purpose of hydrodynamic observations, each expedition taking from 8 to 16 days. Sections at right-angles to the coast and extending out over the continental shelf for more than 100 miles were observed by taking stations (100 in all), at intervals, to obtain various physical and chemical data, so that these could be analyzed and charted to indicate the currents. These sections extend far enough to cross an inshore area, where land-drainage is a seasonal factor, and a second area, where there is a northerly flowing coastwise current, to reach a third area, where more open-sea conditions exist.

On the fourth expedition, a section was observed between the entrance to Johnstone Strait and Cape St. James to further connect up the observations already made off the coast of Vancouver Island and those made off the Queen Charlotte Islands.

Charts embodying the analyses of all of these data have been prepared.

Daily observations of sea-water temperature and salinity, and the atmospheric temperature, precipitation, wind-force, and wind-direction have been carried on continuously at ten points along the coast, between and including William Head, at the south end of Vancouver Island, and Langara Island, to the northwest of Graham Island, Queen Charlotte Islands, and at one point inland on the Fraser River, Poplar Island, near New Westminster. These observations have been correlated with the data obtained in the hydrodynamic measurements. In some cases, new methods of calculation have been devised to make the correlation more nearly complete.

Physical and chemical observations were made by investigators from the Oceanographic Laboratories of the University of Washington and from the University of British Columbia, during a 10-day expedition on the Catalyst, north through the Strait of Georgia, Discovery Passage, Johnstone Strait, Goletas Channel, Hecate Strait, Houston Stewart Channel, up the west coast of the Queen Charlottes, east through Dixon Entrance, south throughout Hecate Strait and Queen Charlotte Sound and southward again to the Strait of Georgia.

Work of the Hydrographic Survey, from the Wm. J. Stewart, was continued on the west coast of the Queen Charlotte Islands and in Rivers Inlet.

Fundamental Biology--Much of the biological investigation and fisheries research done during the year was restricted to the fresh water, but the marine species received some attention.

Extensive collecting by dredging was done during the Catalyst trip, hauls being made at 35 different localities. The material obtained was particularly interesting from the standpoint of distribution. The hydroids obtained in the material have been examined and reported.

The propagation of the Japanese oyster, Ostrea gigas, in Ladysmith Harbor, from stimulated spawning, was especially successful in 1936. Experience now makes it possible to give quite definite assurance of success, if the hydrographic conditions of the water are at all favorable. It has been demonstrated that the oysters artificially stimulated to early spawning recover to prime condition much more rapidly than those that spawn naturally without stimulation. Furthermore, the larvae produced from the earlier spawn grew much more rapidly and were much better able to stand the winter than the later spawn from the natural spawning.

With regard to the success in planting the spat of the eastern oyster, Ostrea virginica, in Boundary Bay, it is definitely indicated that the mortality is least when the spat is obtained from a situation similar, in reference to the tide, to that in which it is planted.

Various devices for collection of spat and methods of exposing cultch were tried out to determine definitely the most suitable type and method.

The study of the life-history of the American Merganser, particularly the feeding habits and food, has been continued. The conclusion is reached that, in certain instances, control-measures are necessary, but when such measures are used, they should be regarded as corrective for a temporary abnormal condition, and not as a permanent policy.

Taxonomic work was confined mainly to the Annulates, Nematodes, and Acanthocephala. The life-history of some of these parasites with alternate hosts has been worked out.

Fisheries--The study of the annual samplings of the sockeye-salmon run to the Fraser, Skeena, and Naas rivers, and to Rivers Inlet was made as usual, although in two of the areas the samplings were less adequate than in other years. The catch of sockeye at Sooke was small in relation to the catch of sockeye at the mouth of the Fraser (Sooke is the sampling point for the Fraser River fish), and a strike of fishermen in the Rivers Inlet Area resulted in the complete cessation of fishing and sampling early in the season.

Experiments were carried out to determine the percentage return from the sea of sockeye-salmon from a known number of seaward migrants.

Further investigation has been carried on with reference to the natural run of pink salmon in Massett Inlet, Queen Charlotte Islands, and to the possibility of building up a run of this species in what is now the off year. Marking experiments have shown that, while the great majority of these fish come back to the parent stream, there are a few strays that go elsewhere.

By reading the scales of specimens of coho-salmon, used in making experiments at many points along the whole coast, it was observed that, while most of the coho (97.89 per cent) lived for approximately one year in fresh water and returned to spawn in the third year, some few of them went to sea in the year in which they were hatched and some stayed in the fresh water for two years; some returned in the second year and some in their fourth year.

The investigation of pilchard followed much the same lines as in previous years but tagging experiments were instituted as well, in cooperation with the California Fisheries Investigation, since there is evidence that at least some of the pilchard migrate backward and forward between the British Columbia and the California waters.

Tagging experiments have been initiated also in connection with the investigation of herring, mainly to see if there is any evidence of extensive migration or of the intermingling of the different races. This was done in connection with the sampling of the commercial catch as it has been carried on in previous years.

The study of the life-history of the ling cod, Ophiodon elongatus, has now been pretty well completed.

An exploratory investigation of vertebra number in capelin indicates sexual dimorphism in vertebra number.

Fisheries technology: Fish oils--Investigation during the year shows that the vitamin-D potency of pilchard-oil decreases as the fishing progresses throughout the season from July to October, whereas the yield of oil per ton of fish ordinarily increases during that period. The effect of geographical variation in vitamin-D potency of oil from pilchards caught at corresponding times is considered negligible.

A similar investigation on dogfish-liver oil has been started but not completed.

The vitamin-D content of herring-oil was determined to see if it could be used to replace pilchard-oil in feeding experiments.

The vitamin-potency of the oil in canned salmon (five species) has been determined and compared.

In determining the vitamin-A potency of halibut-liver oil, a very wide range of values has been encountered.

More extensive analysis of pilchard-oil was carried out. It was determined that the vitamin-D content of the oil was almost completely concentrated in the non-saponifiable fraction. The fatty acid components prepared by saponification were subjected to a detailed analysis that brought out several points of theoretical and practical interest.

Satisfactory results were obtained from further experiments in polymerization to increase the value of marine oils for use in paints, varnishes, and soaps.

Purification of the fatty acid by-products obtained in the production of varnish bases from pilchard-oils was attempted.

Experiments looking to improved methods of "cold clearing" were initiated.

The possibility of chemically condensing pilchard-oil fatty acids to produce antiseptic, emulsifying agents and thermoplastic products (synthetic resins) was investigated.

Handling of fresh and frozen fish: Fresh fish--The formalin treatment of vessels fishing for halibut, developed to minimize the discoloration, has now come into general use with excellent results. The improvement has been enhanced by the introduction of ice-made antiseptic by the use of benzoic acid or other substances having a similar effect, when the ice is being produced.

Frozen fish--Fundamental studies concerning the preservation of quality in cold-stored fish have been continued but have not been brought to a definite conclusion. Much further work has been done on the preparation of glazes for frozen fish, but there is still much room for improvement.

Experimental work on overhead refrigeration of railroad cars has been carried on for some years. During 1936, this was developed far enough to induce the management of one of the transcontinental railroads to build a standard-size railway-car to specifications supplied to provide for overhead refrigeration, and to try it out over a transcontinental route. The results were so satisfactory that other cars of this type will be built, and in time these may replace entirely the end-bunkered refrigeration-cars.

Papers have been published, or are ready for publication, to embody the results of nearly all of these investigations.

[Note--Much of the information for this report was obtained from the Annual Report and the Summary Reports of the Nanaimo Station by the Director, Dr. W. A. Clemens, and of the Prince Rupert Station, by the Director, Dr. N. M. Carter.]

University of British Columbia,
Vancouver, British Columbia, Canada

AMERICAN GEOPHYSICAL UNION

Eighteenth Annual Meeting

SECTION OF VOLCANOLOGY

Washington, D. C.
April 28, 1937

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TUFFS AND OTHER VOLCANIC DEPOSITS OF KATMAI AND YELLOWSTONE PARK

C. N. Fenner

The volcanic activity in the Katmai region in 1912 took two principal forms.

From the central crater of Mount Katmai great volumes of pumiceous ejecta were thrown violently into the air, and fell upon the surrounding country. Large quantities of the finer portions were carried by winds even as far as Kodiak, 100 miles away. Near the volcano the deposits are seen to form loosely coherent strata, 15 or 16 feet thick. The lumps of pumice are not of great size, two or three inches in diameter being an ordinary maximum. Mutual attrition in the air during expulsion was evidently not great, for the angles and corners are only slightly rounded. The looseness and lack of coherence of such deposits permit easy erosion, and they are not likely to be long preserved *in situ*, unless soon covered by more resistant beds. They may be carried out to sea and form extensive but thin strata. Because of this ease of removal and because of original wide-spread distribution, we cannot expect that siliceous pumices, explosively ejected, will ordinarily be represented in their proper relative magnitude among the deposits adjacent to a volcano.

In the Valley of Ten Thousand Smokes the parasitic volcano Novarupta, at one stage of its activity, threw out pumices similar to those of Katmai, but a more important feature of the Valley was the incandescent sand-flow. This appears to have originated in an offshoot of the same magma as that of the central vent of Katmai, which was injected between the nearly horizontal sedimentary strata that underlie the Valley, and broke through to the surface in numerous fissures. Instead of exploding violently and being thrown over the adjacent country by the instantaneous evolution of dissolved gases throughout its mass, it seems to have undergone a less abrupt vesiculation, more in the nature of a continuous and rapid but not explosive frothing, fragmentation, and spewing out, resulting in the somewhat prolonged discharge from the vents of a torrent of comminuted particles (with some lumps), which continued to give off gases for a considerable period. By this prolonged evolution of gas and its mixture with the glass fragments, a high mobility was imparted to the mass. It spread as an incandescent flood down the Valley and came to rest with a surface-slope of only two or three per cent. It covered an area approximately 14 miles in length and several miles in breadth. In places, it shows a thickness of 80 to 100 feet. Even near its lower extremity its temperature was sufficiently high to carbonize trees.

Where sections of the sand flow have been exposed by deep and narrow stream-channels, it shows only a faint stratification. The lumps of pumice and the numerous bits of sedimentary and volcanic rocks contained in it are mingled rather promiscuously with the much greater bulk of fine material. In the lower part of the Valley it has little coherence, and there the fine fragments have the characteristic angular and cusp-like forms of glass shards produced by the disruption of bubbles. In the upper part of the Valley, where the temperature was higher, it is firmly consolidated. A thin section of this material shows, instead of individual shards, a slightly turbid aggregate, permeated by innumerable tiny to cryptocrystalline growths of secondary minerals. In places, these little crystals may be seen, even with a hand lens, encroaching upon small lumps of included glass and replacing them. By further action of this sort the glass has disappeared, and little nests of crystals are left. Where determinable, these are mostly tridymite and orthoclase. These scattered nests of secondary crystals are a minor but very characteristic feature.

We have evidence that the consolidation of the sand-flow material, with its accompanying crystallization, was accomplished shortly after the flow came to rest. The evidence is as follows: In numerous places rather mild secondary explosions occurred, due to two causes, namely, (1) the hot material came into contact with wet ground or streams, or (2) the continued evolution of gases from the part of the magma left underground built up a pressure that cleared the choked vents. In both cases, the material that was piled up around these sites of explosion contain numerous great blocks of sand-flow material, already consolidated at the time of expulsion. It seems that these explosions must have occurred within a few days or even a few hours after the sand-flow was extruded. Thus we are given important evidence of the intensity and rapidity of pneumatolytic action accomplished by the magmatic gases.

This sand-flow represents a form of eruption that apparently had not been recognized before the Katmai occurrence was known. In some of its features it has a close analogy to the nuées ardentes of Martinique and St. Vincent that were described by Lacroix and by Anderson and Flett, but in other respects it behaved quite differently. It seems sufficiently distinct to be termed specifically the Katmaian type of eruption.

Such flows of finely fragmental volcanic material, that spread as thick, nearly horizontal sheets, and form well-consolidated masses, are in a condition to be preserved as members of a geological series. Examples of them have since been recognized in various parts of the world, and there are probably many others. The author believes that this form of extrusion has been of common occurrence.

With the familiarity gained from the study of the sand-flow in the Valley of Ten Thousand Smokes, certain deposits seen in subsequent work in Yellowstone Park have been recognized as probably belonging to the Katmaian type of eruption. Extensive deposits with similar characteristics occur on Gardiner River, south of Bunsen Peak. They are found also on Gibbon River, a few miles east of Madison Junction, and on the trail from Mammoth Springs to Sepulcher Mountain.

Among the many clastic volcanic deposits in Yellowstone Park, a quite different type may be seen in lower Firehole Canyon. A large exposure here seems to represent the feature that, in descriptions of recent lava-flows, has been termed "a moving stone wall." By this is meant the accumulation of heterogeneous fragmental material--large and small blocks mixed with fines--that originate from the disruption of the viscous or rigid front of a slowly advancing flow, and are pushed forward as an assemblage of grinding fragments by the pressure from behind. The exposure in Firehole Canyon is of a rather spectacular sort, as seen on the ground. A thin section of a specimen composed of a breccia of angular fragments in a finer matrix shows recrystallization of the larger pieces, which were originally glassy, and deposition of small crystals in cavities as a result of pneumatolytic action. At Pumice Point, on Yellowstone Lake, similar exposures are found. Portions of the fragmentary breccia here have been welded into a thoroughly indurated but porous mass by the deposition of innumerable tridymite crystals, which are accompanied by little spangles of hematite. The glistening reflections may be seen with the naked eye. The porosity is mostly due to a multitude of small, angular cavities (ordinarily 1/2 to 3 mm in size) lined with tiny crystals. These cavities are a remarkable feature. Specimens of the rock might be said to be made up largely of angular fragments of holes. These were evidently occupied originally by solid material that has been carried away. They have the typical form of glass shards, and, in a few, remnants of glass are still observable as testimony of the character of the original filling. The evidence is strong that the cavities in general represent fragments of glass, whose substance has been almost completely removed by magmatic gases.

These last-mentioned occurrences offer illustrations of rarely described volcanic phenomena. In the exposed sections the larger structures give a picture of the conditions within the mass of fragmental material that frequently forms the front of lava-flows, and their finer features demonstrate the results accomplished by the fuming clouds that issue. From their character and conditions of occurrence, we seem to be justified in believing that solvent and recrystallizing effects were brought about by auto-pneumatolytic gases with a vigor and of a magnitude that many petrologists have hesitated to accept; but the theoretical difficulties that have been expressed should not outweigh the direct evidence. The objections do not appear to be of a fundamental character, but rather to be self-created difficulties that arise from conceptions of the properties of magmas that may themselves be quite hypothetical.

The phenomena so far described relate to certain fragmental deposits formed from rhyolitic lavas. Those mentioned as occurring in Yellowstone Park belong to the most recent epoch of igneous activity, probably of the Pliocene Period. A much older igneous epoch is represented by the great series of deposits termed the Early Basic Breccias, which have been regarded as Miocene or possibly Oligocene. These breccias form the masses of Sepulcher Mountain, Mount Washburne, and Specimen Ridge, which lie not far from frequented tourist routes, but their greatest development is in the rugged Absaroka Mountains in the eastern and northeastern portions of the Park. In places they form deposits several thousand feet thick, some of which are composed chiefly of fragmental material, whereas others have many basaltic lava-flows intercalated.

On first acquaintance with these great deposits two features are likely to attract attention. In the exposures revealed on the precipitous mountain sides the strata have a nearly horizontal attitude for mile after mile (moderate inclination of the beds, seen in places, is probably due in great part to subsequent gentle warping), and many of the beds are made up largely of rounded boulders of great size. What was the means by which transportation and distribution of this material were effected? To one who has chiefly in mind the ordinary text-book illustrations of volcanoes, showing the inclination of beds and the general structure of such typical volcanoes as Vesuvius and Etna, and recalls descriptions of the conditions of extrusion that gave rise to these structures, these two features seem difficult to explain.

Although the structures of Vesuvius and Etna are typical of certain forms of volcanic extrusion, geologists have had impressed upon them forcibly within recent years that other volcanoes that may be considered equally typical depart widely from these in the manner of distribution of their ejecta.

Probably volcanic processes of several kinds were responsible for the building up of the thick beds of basic breccia in Yellowstone Park. We should not suppose that the ordinary explosive ejection of blocks and lapilli was lacking here. The deposits on Mount Washburne and Sepulcher Mountain, for instance, are close to vents, and a portion, at least, was explosively ejected. Probably in general this process was an important factor. This, however, would tend to heap up material close to the vents, and if these accumulations remained undisturbed, we should hardly have the miles of horizontal strata or the rounded boulders that we see.

The formation of the spine of Montagne Pelée, and the accompanying avalanches of clastic material that occasionally burst forth from it in the form of nuées ardentes, have called attention to a type of eruption that has since been recognized as of common occurrence. It is now generally accepted that in such cases very viscous lava is pushed up from a vent in the form of spines, domes, or plugs. At intervals, shattering explosions occur, which disrupt portions of the mass and cause it to rush down the slopes. Continued evolution of gas from the shattered blocks is believed to be an important factor in maintaining mobility, and these streams of fragmental material, carrying large boulders, have been known to continue their course for miles after reaching gentle grades.

By a variation of this process a new element is introduced. In the volcanoes of Java especially, but also in other regions, the waters of crater lakes have been involved in eruptions, and wide-spreading mud-flows have resulted.

Though the evolution of magmatic gases or the presence of water from crater lakes has been definitely recognized as involved in these flows, and must have greatly increased mobility, in other instances boulder-flows of great magnitude have occurred in which only a modicum of water or mud seems to have been present as a lubricating agent, and yet an astonishing facility of movement has been exhibited. A well-known instance is that of the eruption of Bandai San, in Japan, in 1888. This has been attributed to a subterranean explosion, by which a part of the Mountain, of enormous magnitude, was upheaved and set in motion. It flowed down from the Mountain into the lowland, and covered an area of more than 25 square miles.

At the time of the eruption of Mount Katmai, several great boulder-flows or landslides occurred, whose only connection with the eruption seems to have been that the accompanying earthquakes served to start in motion masses of rock that had been in an unstable condition. One of these flows came down the canyon of Mageik Creek and covered the flat floor of Katmai Valley over an area estimated at two miles by three-fourths of a mile. A feature of interest is that it flowed into a forest of cottonwoods, and buried the trunks to a depth of 10 or 12 feet. Though the flow was composed largely of boulders, the trees show little evidence of disturbance. The conditions appear to be closely analogous to those in the silicified forests of Specimen Ridge, in Yellowstone Park, where burial of trees in similar deposits of rounded boulders is evident.

The roundness of the boulders in the Mageik Creek Slide gives the impression that the material set in motion must have been an old glacial accumulation. Material of that kind may have been involved, but observations on another slide indicate that this is not necessarily the case.

A few miles away, a section of steep lava-cliffs on the lower slopes of Mount Katmai fell away, and formed a dam across Katmai River at the upper entrance to Katmai Canyon. This dam persisted for several years, and impounded a lake several hundred feet deep over a wide area. When it gave way, a large part of the dam was swept by the flood through one and one-half to two miles of narrow canyon and spread out over the floor of the Valley at its lower end. The pounding and grinding undergone by the boulders seem to have been equivalent in their rounding effects to those produced on the ordinary boulders of river-channels through hundreds of years of stream-action.

In making application of these various observations to the conditions of accumulation of the Basic Breccia series of Yellowstone Park, and to many occurrences of thick beds of tuffs and breccias in other regions, the point that it is desired to bring out is that a vigorously active volcano forms a structure in which conditions of instability of large masses of rock are likely to occur repeatedly. Material from the interior of the Earth is brought to the surface in great quantity and has to be disposed of. Violent ejection is one means of doing this, but evidently this is only one of the forms that manifestations take. Plugs and domes of viscous material are frequently protruded, which are likely to undergo shattering explosions. Katmaian eruptions may occur. Lavas are poured out, which may be so liquid as to spread for miles but may approach in viscosity that of the plugs, and congeal on steep slopes in unstable positions. Whether an inner explosion shatters a protruded mass and starts it in motion, or whether there is simply the breaking away of a somewhat water-soaked cliff, perhaps accompanied by loose ejecta that have accumulated on slopes, the masses set in motion have an ability to move in their lower courses for long distances over gentle grades in a manner that is difficult to conceive but that is attested by abundant evidence. Landslides of such origin may temporarily impound rivers, and the resulting floods may effect a rounding of boulders and their transportation for many miles. Even torrential rains may have a similar effect.

By a consideration of these and allied processes we are enabled to form a conception of the manner in which such accumulations of fragmental volcanics as those of the Absaroka Range have originated. For some purposes such a general conception may be sufficient, but it would be desirable if geologists would attempt to go further, and determine by a critical examination of the material at hand just what processes produced given results.

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AMYGDALES IN COLUMBIA RIVER LAVAS NEAR FREEDOM, IDAHO

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(Published with the approval of the Director, U. S. Geological Survey)

Incomplete study of seven amygdales from the Columbia River lava-flows along Slate Creek, a tributary of Salmon River, near Freedom in north-central Idaho, reveals that these small objects are of unusual geological and mineralogical interest. This paper includes an outline of the geology of the area from which the amygdales came, a description of the amygdales, and a brief account of the periodic tilting of a large fault-block as revealed by them.

Slate Creek enters Salmon River near the eastern border of the Columbia Plateau. In this locality the thick Lower Middle Miocene lava-flows of the plateau country are interbedded with the sediments of many local lakes formed periodically as successive flows dammed the streams flowing westward from the higher country to the east. A section measured near the mouth of Slate Creek shows the volcanic rocks there to be 2800 feet thick. At some places on the Plateau farther from its borders the flows aggregate more than twice that thickness.

The plateau-surface in north-central Idaho is considered as being essentially a flow-surface now locally warped, faulted, and dissected. The general altitude of the Plateau approaches 3000 feet. Near its eastern border, however, the surface rises eastward toward the adjacent Clearwater and Salmon River Mountains and locally attains altitudes of more than 7000 feet. Apparently the lava-plateau has subsided, in places several thousand feet, since the flows poured out. In many places westward-dipping fault-blocks carry the surface from its elevated position on the mountain slopes to, and locally far below, the general plateau level.

The Slate Creek area forms part of one of these fault-blocks, the Whitebird Block (Fig. 1). The Whitebird Block is about 15 miles long in a northward direction parallel to its main bounding faults and from about 12 to about 15 miles wide.

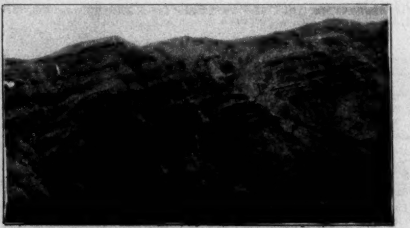
FIG. 1—VIEW NORTHWARD ACROSS SLATE CREEK CANYON SHOWING TILTED LAVA-FLOWS OF THE WHITEBIRD FAULT-BLOCK

The two principal normal faults on the eastern edge of the Whitebird Block have a combined displacement of about 1000 feet. The similar fault that limits the Block on the west roughly parallels Salmon River and the two sides there show a relative vertical movement of at least 3500 feet. The east is the downthrown side in both cases.

The surface of the Block, except where it has been dissected by Slate, Whitebird, Skookemchuck, and some other creeks, constitutes essentially a plane whose upper eastern edge along the top of the main eastern fault-scarp lies at a general altitude of about 6000 feet. This plane, which is nearly parallel to the flows, dips westward in the Slate Creek Area at

17° but at smaller angles elsewhere and along its western lower edge abuts, at an altitude of about 1800 feet, the scarp that rises steeply along the western bounding fault to the Salmon River-Snake River divide about 5500 feet above sea-level.

In the Slate Creek Area individual flows range from about ten to more than 100 feet thick. The series is composed of about 35 flows with an average thickness of about 65 feet. The rest of the 2600-foot section is made up of interbedded, mostly unconsolidated sediments. The exact number of flows present and the exact number and thicknesses of the sedimentary strata could not be determined because of imperfect outcrops, the difficulty of separating some flow-sequences into their individual parts, and the fact that the sediments are largely concealed beneath lava talus slopes.

Most of the flows are massive in their lower parts and have scoriacious tops. Some are vesicular throughout.

The amygdales with which this paper is principally concerned are distributed in the Slate Creek Area throughout the lava-series. The bodies range from tiny amygdales a fraction of an inch in diameter to amygdales several inches across. They are confined throughout to the vesicular parts of the flows and in this, as well as in shape, they are identical with unfilled gas cavities or vesicles. Locally hundreds of them occupy small rock-volumes.

Some, particularly the smaller ones, are nearly spherical. Others are flattened ellipsoids and still others have nearly circular cross-sections parallel to the flows but are elongated along axes at nearly right-angles to the flows. A few are crudely cylindrical, and the longer axes of the cylinders form different but steep angles with the flows. All are somewhat flatter on the bottom than they are on the top or sides. The inference seems justified that gases were exuded by the solidifying lava, that some of the gas collected into bubbles which expanded and moved, principally upward, in the congealing mass until prevented from doing so farther by the solidification or at least the greatly increased viscosity of the melt.

The lava-floods spread far and wide from their fissure sources since individual flows, without any apparent change, can be traced for many miles in the canyon-walls of the Snake, Salmon, and smaller streams. The scoriacious tops of most flows are broken into countless fragments recemented by later scoriacious lava. Apparently the lava of a typical flow was not very viscous, flowed rapidly, and was continually frothing on top. The solidified froth was constantly being broken and stirred into the travelling melt beneath until the flow finally froze or ceased moving because it had reached its own level on the bounding slopes.

In contrast to this method of giving up gas, the vesicles in the more massive lava beneath the scoriacious tops indicate that the gas bubbles formed when the lava was stagnant, or nearly so, and relatively viscous, that is, late in the consolidation history of any individual flow.

Each of the seven amygdales collected is enclosed in a series of thin concentric shells of mineral matter that range in aggregate thickness from less than a millimeter to more than ten mm. Each amygdale exhibits the same sequence of mineral bands, in other words, the formation of the shells was accomplished by a general process applicable to the whole lava-series. Small lava-fragments in the amygdales are each surrounded by identical concentric layers. The concentric bands possibly were formed by deuteric emanations into the vesicles from the hot surrounding lava-mass.

The amygdales are characterized by several layers as follows inward from the enclosing country rock: A nontronite layer, a greenalite layer, a melanophlogite layer, an erionite layer, a chalcedony layer, and a layer of mixed chalcedony and opal. The greenalite layer is absent locally in some specimens, and in several specimens the chalcedony layer and the chalcedony-opal layer are repeated several times.

The mineral,believed from its optical properties to be nontronite, a hydrous silicate of calcium, magnesium, and ferric iron, forms a yellow, red, or brown waxy surface on the outside of the amygdales and around rock-inclusions in the amygdales. In many places the outer surface of the nontronite layer, that is, the surface toward the rock, is marked by small nearly hemispherical depressions. In these depressions and distributed through the nontronite are small quantities of other minerals not yet determined with certainty. Among these are gypsum, found in flat-curving hairlike blades matted in some of the pits; an unidentified white powdery mineral; a bright orange powdery mineral; and a red birefringent mineral with high indices of refraction that may be hematite.

The nontronite layer is followed by a layer of greenalite, a hydrous silicate of ferrous iron. The greenalite layer consists of a mass of tiny, bright green, spherical masses. Moss-like and botryoidal masses of greenalite are sparingly present in layers inside of the main greenalite layer.

Melanophlogite, which consists largely of silica with some sulphur trioxide and water, is a rare mineral about which little is known. The thin, right-angled, isotropic crystals, identified as this mineral because of their optical properties, make up a layer of variously oriented blunt laths next to the greenalite layer if it is present and to the nontronite layer if it is not. In this melanophlogite layer are found locally many larger crystals having the shapes of anhydrite (anhydrous calcium sulphate) and glauberite (a sulphate of sodium and calcium). In the section shown by Figure 2 the large diamond-shaped crystal slightly to the right and above the center of the photograph resembles a glauberite crystal in shape; the large lath-shaped crystal slightly to the right and below the center resembles in shape an anhydrite crystal. Both of these crystals are in the thin melanophlogite layer, which is distinguished by its mosaic-like texture. The melanophlogite layer completely surrounds the diamond-shaped crystal but does not extend around the interior end of the lath-shaped crystal.

It is suggested that the larger crystals are pseudomorphs after anhydrite and glauberite. W. T. Schaller (personal communication) noticed the similarity in shapes to some of the cavities from the New Jersey Zeolite Region which are known to be moulds of those minerals and he has suggested that the anhydrite and glauberite, if the shapes do indeed indicate the former presence of those minerals, were formed from material picked up by the lava-flows from the periodic lakes already mentioned and which later crystallized from the melt as he proved (U. S. Geol. Surv. Bull. 832, 1932) to be the case in New Jersey (see Fig. 3 which is from his Plate 23A).

The erionite layer is readily distinguished optically even with plane-polarized light by its smoky appearance and low index of refraction. Erionite like melanophlogite is rare and little known. It belongs to the zeolite group and is a hydrous silicate of calcium, sodium, potassium, and aluminum. The grinding of the thin section illustrated in the photomicrograph of Figure 4 resulted in the removal of all the edges outside the erionite layer. The erionite consists of tiny needles oriented at right-angles to the concentric layers. The radiating needle-like structure is not apparent except with crossed nicols and hence does not show.

Radiating typical chalcedony-needles and narrow bands containing some opal, which define the concentric layering, constitute the innermost layers (Fig. 4). Locally opaline layers are broken into lines of hemispheres flat on the side toward the periphery and spherical toward the interior of the amygdale. Under high magnification these hemispheres are seen to be made up of radiating needles. The rounded inner surfaces and the flat outer surfaces of the hemispheres seem to indicate restricted growth on the chalcedony layer and free growth into the cavity.

Locally the innermost layers consist of radiating coarse quartz crystals.

Inside the group of concentric layers the amygdales are composed of parallel or nearly parallel layers of silica. Some of the layers are sharply defined, others are gradational and discontinuous. The layering is caused by alternations of gray translucent material and white opaque material. In Figure 5 the thin group of concentric layers already described is present along the right side of the polished section and around the one large and several small pits near the bottom; the pits were formed by the removal of lava-fragments. The bar scale represents 50 mm.

Microscopic examination shows the translucent material to be quartz and the opaque to be opal or a mixture of opal and quartz. Most of the quartz layers show at least a sparse distribution of opaline nuclei and some are literally full of small masses of opal giving the appearance of a blinding snowstorm. Under crossed nicols the quartz shows a variety of textures including coarse-granular, fine-granular, needle-like, plumose, and flamboyant.

The upper surfaces of the opaline bands are much more regular than the lower surfaces. Microscopic examination shows the irregularity of the lower surfaces to be due to complete or fragmentary shells of opal around ellipsoidal masses of quartz. In Figure 6 note the extreme irregularity of the bottom of the opaline layer and the dark ellipsoidal bodies of quartz principally in the lower part of the opaline layer.

The layers in the interiors of many of the amygdales are not mutually parallel but converge somewhat. The convergence in the seven specimens collected ranges from complete parallelism to a maximum of 14°. In Figure 7, although the maximum convergence of layers can not be seen be-

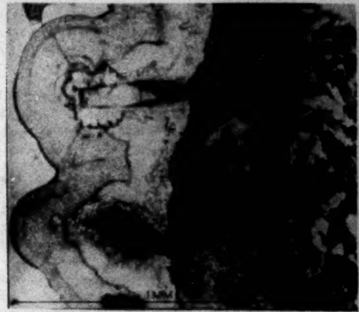

FIG. 2—SECTION ACROSS ALL CONCENTRIC LAYERS OF AN AMYGDALE FROM LAVA (LEFT) INTO INTERIOR (RIGHT)

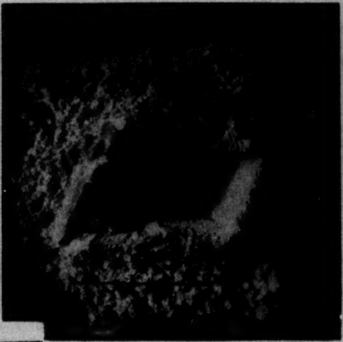

FIG. 3—CAVITY FORMERLY OCCUPIED BY GLAUBERITE FROM THE NEW JERSEY ZEOLITE REGION

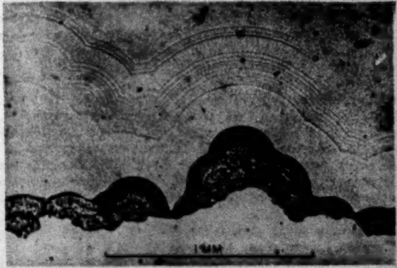

FIG. 4—ERIONITE LAYER (DARK LAYER AT BOTTOM), CHALCEDONY LAYER, AND LAYER OF MIXED CHALCEDONY AND OPAL

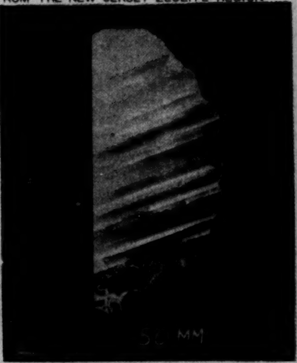

FIG. 5—POLISHED SURFACE OF AN AMYGDALE SHOWING ALTERNATING BANDS OF GRAY TRANSLUCENT QUARTZ, WHITE OPAL, AND A WHITE MIXTURE OF OPAL AND QUARTZ

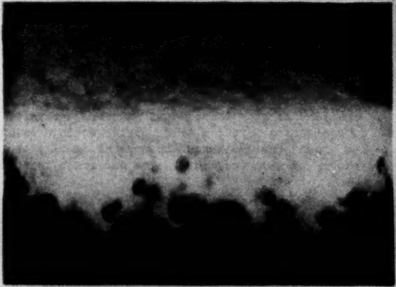

FIG. 6—PHOTOMICROGRAPH OF POLISHED SURFACE OF PART OF INTERIOR OF AN AMYGDALE SHOWING A WHITE OPALINE LAYER, A GRAY LAYER OF QUARTZ THAT CONTAINS SOME OPAL ABOVE IT, AND A DARK GRAY LAYER OF QUARTZ BELOW IT

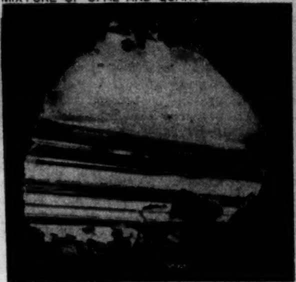

FIG. 7—POLISHED SURFACE OF SECTION CUT THROUGH AN AMYGDALE SHOWING CONVERGENCE OF INTERIOR LAYERS

cause of the direction in which the section was cut, it is known to be 14°. In this convergence of the interior layers lies the story of the tilting of the Whitebird Block.

It was stated above that the lava-flows now dip at 17° in the Slate Creek Area and that the amygdales are present throughout the lava-section. Since the top flow and the bottom flow are parallel, there was no tilting before the top flow was poured out. Evidence has been given showing that the lava was not very viscous when the flows spread over the country. Therefore, there was probably little, if any, initial dip.

The flows are known to be Lower Middle Miocene. Wide-spread moraines, earlier than the Wisconsin moraines, cover some areas of tilted lava on the lower parts of some of the higher down-faulted blocks and are not disturbed by structural movements. Therefore, the tilting was after the Lower Middle Miocene and before a pre-Wisconsin glacial stage.

The lower layers of all the amygdales studied, that show any convergence of layers, are without exception more nearly parallel to the flows than the upper layers which are either horizontal or inclined in the same direction as the flows in the angle between the horizontal and the dip of the flows. None of the amygdales shows a convergence as great as the 17° dip of the lava. The amygdale in which the layers show the 14° convergence reflects almost the complete tilting history of the Whitebird Block. Other amygdales showing smaller convergences of the layers probably either were filled before the tilting was complete or received no deposition until after some tilting had taken place.

It is tentatively concluded that the layers are the result of the successive deposition of silica in cavities long after the concentric shells around the cavities were deposited from deuteric emanations. It is further concluded that the layers of the interiors were deposited horizontally under the influence of gravity and that the convergence of the layers is due to periodic tilting of the Whitebird Block during and between the times of deposition of successive layers of silica.

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EXTRAORDINARY TOPAZ-REPLACEMENT BODY IN THE BREWER MINE, SOUTH CAROLINA

Jewell J. Glass

(Published with the approval of the Director, U. S. Geological Survey)

Introduction--A large body of massive topaz forms a part of the gold-bearing lode at the Brewer Mine, South Carolina. This gold-mine was opened 100 years ago and merits the distinction of being one of the early gold-discoveries of the Southern Appalachian Region. The Brewer Mine is located near Jefferson, in Chesterfield County, near the northern boundary of South Carolina, and on the eastern edge of the Piedmont Province.

The country rock is described by J. T. Pardee and C. F. Park, Jr., (Gold-deposits of the Southern Appalachians, U. S. Geol. Surv. Prof. Paper, in preparation) as a quartz-sericite schist that locally preserves the structure of a fine-grained, waterlaid tuff, probably a rhyolite, from which it was derived. Exposures of granite that intrude the schist appear on the north and west at distances of a mile to a mile and a half.

The lode extends nearly half a mile along a broad ridge about 200 feet high, between Little Fork Creek and Lynch's River. It is a large body composed chiefly of fine-grained quartz that shows the pattern of a breccia that it has replaced.

During a century of intermittent mining operations several pits have been excavated, one of them 300 feet wide and 140 feet deep. The largest excavation, the Brewer Pit, shows a weathered zone of 40 to 60 feet in which much of the quartz has disintegrated to a very fine white sand. Other less friable bodies have the structure of a breccia cemented with iron oxide. Both the sand and the cemented bodies carry particles of free gold and scattered grains of topaz.

At greater depths the rock is firm and flint-like and contains two to five per cent of pyrite. Assays of several samples from the Brewer Pit showed from 0.04 ounce to 0.13 ounce of gold per ton. The dense quartz-rock also contains scattered grains of topaz. This fact was suspected by L. C. Graton (Reconnaissance of some gold and tin deposits of the Southern Appalachians, U. S. Geol. Surv. Bull. 293, pp. 90-91, 1906), who examined the deposit in 1906. He men-

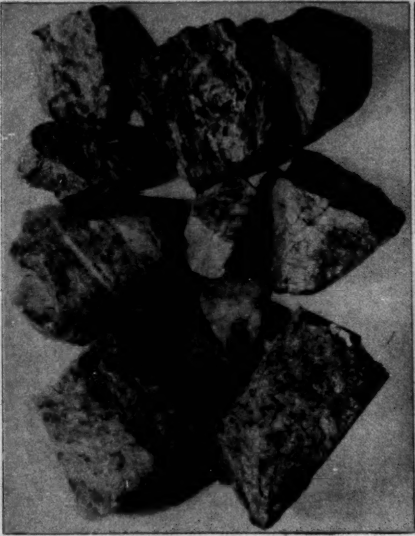

FIG. 1—LOOSE, SMOOTH-FACED BLOCKS OF TOPAZ ABOUT SIZE OF HALF BRICK, SOME HAVE FORM OF PYRAMIDS AND WEDGES, SOME SHOW WHITE WAVY BANDS IN GRAY MASS—REPRESENTING THE STRUCTURE OF A ROCK THAT THE TOPAZ REPLACED

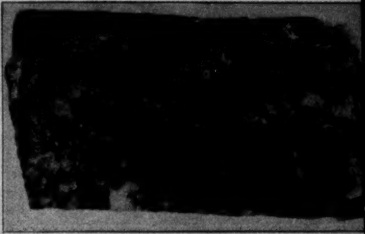

FIG. 2—POLISHED SURFACE OF INTERIOR OF ONE OF T
TOPAZ BLOCKS SHOWING PATTERN OF A BRECCIA TH
HAS BEEN REPLACED BY TOPAZ

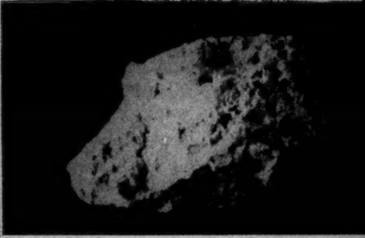

FIG. 3—A FRIABLE SPONGE-LIKE MASS OF TOPAZ (THE
AGGREGATE CONSISTS OF SMALL CRYSTALS AND ROUN
GRAINS LOOSELY HELD TOGETHER FROM WHICH CEME
TING MATERIALS HAVE DISSOLVED OUT)

tions the quartz as "penetrated by numerous prismatic crystals, apparently of secondary origin, possibly topaz."

The massive topaz--The topaz rock mass which forms a large part of the gold-bearing lode crops out just north of the Brewer Pit. Exposures in place occupy an area about 25 feet wide and 50 feet long, but a greater extent of the body is indicated by the distribution of "float" on the slope above the outcrop. No attempt has been made to determine the extent of the topaz body. Loose fragments about the size of half a brick are abundant in the waste heaps of placer pits along the slope below (see Fig. 1). The rounded edges of some of the fragments may be due to their use as riffle-blocks in the washing apparatus of early placer-mining. In general appearance the topaz resembles the undecomposed quartz-rock of the lode. In fact, the two look so much alike that in a cursory examination they are not likely to be distinguished from one another unless the relative specific gravity (3.5) of the topaz is noticed. Some of the specimens of topaz show the pattern of a breccia, as is clearly shown in Figure 2, and others are marked with wavy lines or bands representing the structure of a rock that the topaz has replaced. Contact-relations of the two indicate that the topaz is later than the quartz-rock.

The topaz mass is not mentioned in previous reports of the Brewer Mine. Apparently it has been classified heretofore as "flinty quartz," a conclusion not to be wondered at since its texture is very similar to that of flint or chert. It has a waxy luster and hardness about seven. It breaks with a conchoidal fracture and separates along joints into small smooth-faced blocks, some of which have the form of pyramids and wedges. It is sub-translucent and prevailingly gray, and commonly it is mottled or streaked with white cloud-like bands. Some of the weathered surfaces show the staining of iron oxide which appears to be due to the oxidation of small inclusions of pyrite. As shown by the chemical analysis, however, the actual amount of iron present is small. A sample yielded 0.01 ounce of gold per ton by assay.

The exceedingly fine grains that make up the massive topaz are only a few microns in diameter and closely resemble the granules in a fine-grained chert. On account of its fine-grained character only the mean index of refraction could be determined on the massive topaz; this is n = 1.631, which corresponds to β in the more coarsely granular variety, and thus indicates the same composition.

Chemical analysis--The massive topaz was analyzed by R. E. Stevens at the chemical laboratory of the United States Geological Survey, and his results are given in Table 1.

Table 1--Analysis of the massive topaz from the Brewer Mine, South Carolina

SiO_2	33.00
Al_2O_3	56.76
Fe_2O_3	trace
H_2O-	0.04
H_2O+	2.67
F	13.23
	105.70
Minus O = F	5.57
	100.13
Specific gravity	3.509

The analysis is substantiated by the low specific gravity and by the optical properties. From a review of the literature, it appears that the Brewer material shows the lowest fluorine- and the highest water-content of any topaz yet described. One analysis of topaz from Utah shows water = 0.19 per cent and fluorine = 20.00 per cent with specific gravity = 3.5.

Granular and disseminated topaz--In addition to the massive topaz described, the Brewer lode contains disseminated fine grains, and, in places at least, aggregates of coarser grains as shown in Figure 3. Specimens from a boulder found in an old placer working (Tanyard Pit) about 1000 feet south of the Brewer Pit are aggregates of white granular topaz from which some other more soluble mineral or minerals have been dissolved. The mass has a sponge-like structure. The loose aggregate consists of clear colorless interlocking grains about 0.5 mm in diameter. Apparently all cementing materials have disappeared and the mass is friable enough to be crushed with the hands. A few spots of iron oxide suggest that pyrite at one time occupied at least some of the spaces, indicating that the replacement by topaz was incomplete.

An optical study of the granular topaz grains in thin section show a more or less rounded outline; a few grains, however, show euhedral form. Many of the larger grains contain nuclei of topaz that apparently represent preexisting grains enlarged by later addition of topaz. The amount of impurities is small and the loose granular aggregates are essentially pure topaz.

The individual grains are colorless and transparent. Their optical axial angle, + 2V = 45° to 48°, is unusually small for topaz. The indices of refraction were determined by the immersion method in white light and are: $\alpha = 1.629$, $\beta = 1.631$, $\gamma = 1.638$.

The small optical axial angle and the high indices of refraction indicate that the granular material has the same low fluorine- and high water-content as the massive topaz.

It has been shown by S. L. Penfield and J. C. Minor, Jr., (On the chemical composition and related physical properties of topaz, Amer. J. Sci., 3d ser., v. 47, p. 387, 1894) that the variation which topaz shows both in chemical composition and physical properties results from an isomorphous replacement of fluorine by hydroxyl. As the hydroxyl replaces fluorine, the value for 2V decreases. This relation is so constant that the percentage of water can be calculated from the value of 2V. Likewise the indices and the strength of the double refraction show a progressive change. As the OH replaces fluorine, the indices of refraction increase and the strength of double refraction decreases.

Other examples of massive topaz--Topaz is commonly regarded as a pegmatite mineral. A remarkable example of massive topaz, although showing crystal form and found in pegmatite in Colorado, is cited by E. B. Eckel (A new lepidolite deposit in Colorado, J. Amer. Ceramic Soc., v. 16, No. 5, p. 239, 1933).

A very interesting example, and a more comparable one to the Brewer material, is the topaz greisenization of granite described by J. T. Singewald, Jr., and Charles Milton (Greisen and associated mineralization at Silver Mine, Missouri, Econ. Geol., v. 24, No. 6, p. 574, 1929). In a description of the greisen at Ozark Mine they say, "The rock looks like a dense, fine-grained gray quartzite. Under the microscope it is seen to consist of topaz and quartz. In some of the rock the quartz is so subordinate in amount that it consists almost entirely of topaz."

Conclusion--The enormous amount of massive topaz at the South Carolina occurrence exhibits a unique phenomenon of mineralization and is one of the most noteworthy examples of "topazization" ever recorded. Solutions rich in fluorine, silica, and sulphides, and deficient in alkalies, reacted with the previously existing rocks and replaced them with topaz, quartz, and sulphides. The introduction of silica, sulphides, and even of fluorine is not unusual in mineral deposits. On the other hand, the large-scale introduction of Al_2O_3 that is represented by great amounts of topaz, such as is found at the Brewer Mine, and the deficiency in alkalies that is shown by the almost total absence of feldspars is unusual. Perhaps the formation of corundum as a late replacement-process in certain pegmatites is a related type of mineralization and the presence or absence of fluorine may be a factor in determining the minerals that are deposited. Thus the Brewer Deposit presents an unusually interesting problem in the chemistry of mineralization. The data, however, are too meager as yet to permit a detailed consideration of the chemistry of paragenesis.

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SILICATE-WATER SYSTEMS: "OSMOTIC-PRESSURE" PHENOMENA AND THEIR BEARING IN SOME PROBLEMS OF IGNEOUS ACTIVITY

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The problem of determining the solubility of water in silicate-melts when the two phases are subjected to the same confining pressure has occupied our attention for some time and results from such work have been presented to the Section of Volcanology on previous occasions. There is, however, another important aspect of this work that merits attention, namely, the evaluation of the solubility-relations when the hydrostatic pressure is not the same on the two phases, water and silicate solution. This second case is also of importance in problems associated with volcanism and certain other aspects of igneous activity.

If the country rock surrounding a magma were pervious to water but impervious to the silicate solution, then the magma would be under a confining pressure equal to or greater than that due to the weight of overlying rock, whereas the water would be under a confining pressure equivalent approximately to its own hydrostatic head.

A direct determination of the solubility-relations under such conditions would be very difficult to carry out experimentally. They were therefore obtained thermodynamically from other determined properties of the systems. The necessary mathematical relations are derived in a previous paper (Amer. Min., v. 22, pp. 485-490, 1937). To evaluate them the pressure-volume diagram of water was obtained for the 1000° isotherm. From this curve the fugacity-ratios were then calculated and correlated with the activity-ratios of the water in solution in the silicate-melt. The relation of activity to concentration was obtained from experimentally-determined solubility and freezing-point curves for the system albite-water. These data are presented in Table 1. The confining pressure on the water phase, p_0, expressed as bars (10^6 dynes/cm^2), is given in column 1. The osmotic pressure $\pi = (p - p_0)$ of albite-water solution in column 2 is expressed as a function of the water in solution, denoted as weight per cent in column 3, for different silicate-solution confining pressures, p, at 1000° C. In column 4 are given the experimentally-determined solubility-relations for the case where the two phases are under the same confining pressures, $p = p_0$.

Table 1

p_0, bars	$\pi = (p - p_0)$ bars	Wt. per cent water in solution	Wt. per cent water in solution for $p = p_0$
		p = 4000 bars, T = 1000° C	
4000	0	9	9.0
3000	1000	4	8.3
2000	2000	3	7.4
1000	3000	1	5.5
		p = 3000 bars, T = 1000° C	
3000	0	8.3	8.3
2000	1000	3.5	7.4
1000	2000	1.4	5.5
		p = 2000 bars, T = 1000° C	
2000	0	7.4	7.4
1000	1000	2.5	5.5

A magma can thus become supersaturated with respect to water either by lowering the confining pressure on the silicate-solution or by making the confining walls porous to the water-component. In either case a separation into two fluid phases will take place. In the first case, however, separation of the water-phase will occur by vesiculation, whereas in the second case water will separate out only by diffusion out of the magma; the latter is therefore a slower process.

This limited miscibility of water may at times play important roles in igneous activity and some possible situations will now be considered.

In the Hawaiian Islands an elevation of about 12,000 feet above sea-level represents approximately the maximum height of rise of the craters. The equivalent height above the crustal surface is then about 5.5 km (12,000 feet plus 2/3 of the oceanic depth or a total of 18,000 feet). If we furthermore assume a change of ten per cent in density on crystallization, a column of this height would need a depth of about 50 to 60 km for compensation; the root of the magma-column would lie at this depth. It is rather interesting that this depth should coincide so well with the crustal thickness estimated from other considerations. A magma could then approach the surface and yet be under a pressure of about 1500 bars. This is equivalent to a 5-km additional thickness of overlying rock-mantle. As the magma approached the surface, this excess inherent pressure of the magma would be sufficient to arch and fissure the overlying rock-structure. The presence of excess magmatic pressure is corroborated by other igneous phenomena such as the existence of sills and laccoliths wherein the overlying rock-structure has been bodily pushed upward.

Suppose now that a magma containing water, of concentration equivalent to a saturation-pressure of 4000 bars (nine per cent), and surrounded by an impervious wall rock, were to approach to within two km of the surface. If the country rock remained impervious to the magma-components and strong enough to retain them when it had approached to a depth of two km, the pressure would have fallen to 2000 bars (1500 plus 500 bars). At this pressure some of the water would separate from solution with vesiculation, but this separation into two fluid phases, the water-phase consisting of about 1.6 per cent by weight, would increase the total volume by only about two to three per cent. The initial fissuring and shattering would thus seem to be dependent on the existing differential pressure, that is, the difference between the magma-pressure and that due to the weight of overlying rock which, as estimated herein, may be as high as 1500 bars. As soon as this excess pressure is released, more of the water-phase would form with continued vesiculation and the total volume would approximately double. The work term $p \Delta v$, resulting from this latter effect and amounting to about 75 ft-lbs per gram of magma, would cause further explosive phenomena and be accompanied by continued increase in and expansion of the water-phase. Under some conditions this latter effect would result in formation of pumice and volcanic ash.

It will also be evident from Table 1 why rock glasses containing any considerable quantity of water in solution should be exceedingly rare. It was first found by Dr. E. S. Shepherd that clean obsidians containing about one per cent or less of water retain most of this water as they are heated until a temperature of about 850° is reached, when the glasses swell up into a pumice many times the volume of the original glass. On the other hand, rock glasses containing several per cent of water start giving off water as soon as heated and continue to give off most of their water at temperatures in the neighborhood of 200° to 300° at a rather rapid rate. It appears then that water may be present in at least two different states. The inference is that water in small concentrations is retained in solution in rock-forming silicate glasses whereas, for rock glasses of high water-content, part of the water may be present as a separate phase in the glass block. Additional evidence for this conclusion is given by the fact that glasses of high water-content are generally perlitic in structure, which is a fracture structure, and are not clean in appearance as are the glasses of low-water concentrations.

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A PRIMARY ULTRAMAFIC MAGMA

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Introduction--The results of the work of several years are here presented in much condensed form. The material will be expanded at some late time into a more complete treatment of the problem. The broader factual data are set down in outline in the first section. Certain conclusions are drawn from them in the second section, but supporting detailed evidence has been omitted. Until this is presented the conclusions must naturally remain tentative.

There can be little doubt that certain peridotites are products of crystallization differentiation of basaltic magmas brought about by separation in one manner or another of the early formed crystals, olivine and pyroxene, from the remainder of the basalt-magma. The peridotites of Skye described by Bowen [see 1 of references at end of paper] seem clearly to be of this origin as are, in the writer's opinion, the ultramafic zones of the Bushveld and Stillwater lopoliths. This type of peridotite is not under consideration here.

The ultramafic intrusives here being discussed are more or less serpentinized and occur abundantly in the present island arcs and in all major orogenic belts of the world. They form one member of those "green rocks" which the Europeans have lumped (inconveniently) under the heading of "ophiolites." They comprise the greater part of all the world's peridotites.

Observed relations: (1) Distribution--The serpentinized peridotites of the type under discussion occur in strongly deformed orogenic belts and are not found elsewhere.

(2) Age-relations--They seem to be intruded during the first great deformation of the belt, and they seem to be less common in the Pre-Cambrian than in more recent time.

(3) Shape--The majority of these intrusives are concordant lenses; coalescing lenses forming pinching and swelling sheets, sills, and irregular stock-like bodies are common shapes of the smaller masses. The larger bodies of batholithic proportions seem to occur at the cores of anticlinal structures, suggesting phacolithic forms. Dikes are not very common except along fault planes.

(4) Lack of associated igneous rocks--Large areas of serpentinized peridotite occur in many cases without other igneous rocks of the same period of igneous activity; that is, Camaguey batholith in Cuba 2500 + square miles; also large areas in California, southeast Borneo, central Celebes, parts of Vermont and southern Quebec, as well as many other localities. (If these were differentiates of a basaltic magma, huge masses of complementary more felsic igneous rocks ought to be present, and gradations from peridotites to felsic rocks should be fairly common.)

(5) Border facies--The border facies of these peridotites is also peridotite of practically the same composition as the main masses, differing from them only in texture and in many cases in degree of serpentinization. In no body seen by the writer has a border facies of olivine basalt porphyry, such as Bowen [1] has described for the peridotites of Skye, been found.

(6) Effusive facies--These peridotites are quite common as near-surface intrusives, but an effusive facies seems to be almost entirely lacking (on theoretical grounds it is not surprising that this is so). Certain examples of an effusive facies, however, do exist, the best example of which seems to be the breccia pipes described by Koolhoven [2] associated with a batholithic peridotite massif in Borneo.

(7) Lack of contact-metamorphism [3]--They produce remarkably little contact-metamorphism on their wall rocks. Small intrusives (up to 500 feet across) produce no noticeable effects at their contacts. Moderate-sized ones may produce a slight induration. Bodies two or three miles across have been observed to have a contact-aureole about 150 feet thick, the inner part of which is hornfels which grades outward rapidly into phyllitic rocks. (A basaltic magma of equal proportions might be expected to produce a metamorphic aureole hundreds or even thousands of feet across.) No hydrothermal effects are noted; the type of metamorphism seems to be purely thermal.

(8) Differentiation--As a rule, these intrusions show remarkably little variation that might be ascribed to magmatic differentiation. Areas of fresh, unserpentinized peridotite, dunite or pyroxenite (commonly bronzitite or websterite) may be noted. Very small segregations of allivalite (bytownite plus olivine), grading into picrite and hence to peridotite, are found in the large intrusives, but have a minute size compared to the bulk of the intrusive. Segregations of chromite or picotite in lenses, veins, or irregular masses are common, but again of small bulk. Feldspathic peridotites are only rarely associated with this type of intrusive.

(9) Difference with depth--The peridotites now found in the deeply eroded roots of the orogenic zone (in anhydrous gneisses) seem in general to be less serpentinized than those intruded at higher levels in unmetamorphosed water-bearing sediments (that is, North Carolina [4], Sweden [5], India [6]).

(10) Accessory minerals--Such minerals are extremely rare except for the picotite and chromite already mentioned and magnetite associated with serpentinization. Minute amounts of platinum metals are often present. Diamonds have been noted in a few instances. Sulphides are not common. Titanite, apatite, zircon, ilmenite, and rutile are absent. Garnet peridotites are not uncommon, but the garnet may be a product of either later metamorphism or contamination of the magma. Brucite may be a late-stage primary mineral in some cases.

(11) Secondary iron-rich peridotites--Strong evidence of the formation of a peridotite magma relatively richer in iron by "reworking" of a crystal-settled peridotite from a basalt magma was observed in the Stillwater Complex of Montana. Dikes and pipes of this secondary peridotite intrude overlying rocks. These are probably analogous to the hortonolite dunites of the Bushveld.

(12) Chemical composition--A great similarity between average analyses of these peridotites from such areas as the Alps, Scandinavia, Newfoundland, Cuba, the Appalachians, Southern Rhodesia, may be noted. The average of a number of such peridotites from a given area in practically all cases has a total iron content (calculated as FeO) of less than ten per cent and usually between six and eight per cent. In contrast to this, those peridotites formed by crystallization differentiation from basaltic magmas (Bushveld and Stillwater), so far as can be ascertained from the few analyses available, have an iron-content of a little over 11 per cent as a rule, and the secondary peridotites formed from them range from 13 per cent all the way to 38 per cent total iron as FeO. P_2O_5 and TiO_2 are usually very low, and Cr_2O_3 and NiO_2 are always present in appreciable amounts.

Conclusion--All peridotites have been considered by some to be differentiation products of a basaltic magma. The chief reasons for this are three: (1) The demonstration that certain peridotites have a border chill facies of olivine basalt; (2) the absence of an effusive equivalent; and (3) the high temperature which a peridotite-melt should have.

The peridotites here under consideration have a border facies of peridotite, and do have an effusive facies though it is rare. The relatively low temperature of this peridotite magma is difficult to account for though its demonstrated high water-content is probably the cause.

A number of other conclusions may be drawn from the above data, but will not be considered at this time.

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BASIC ROCKS IN THE EASTERN PENNSYLVANIA HIGHLANDS

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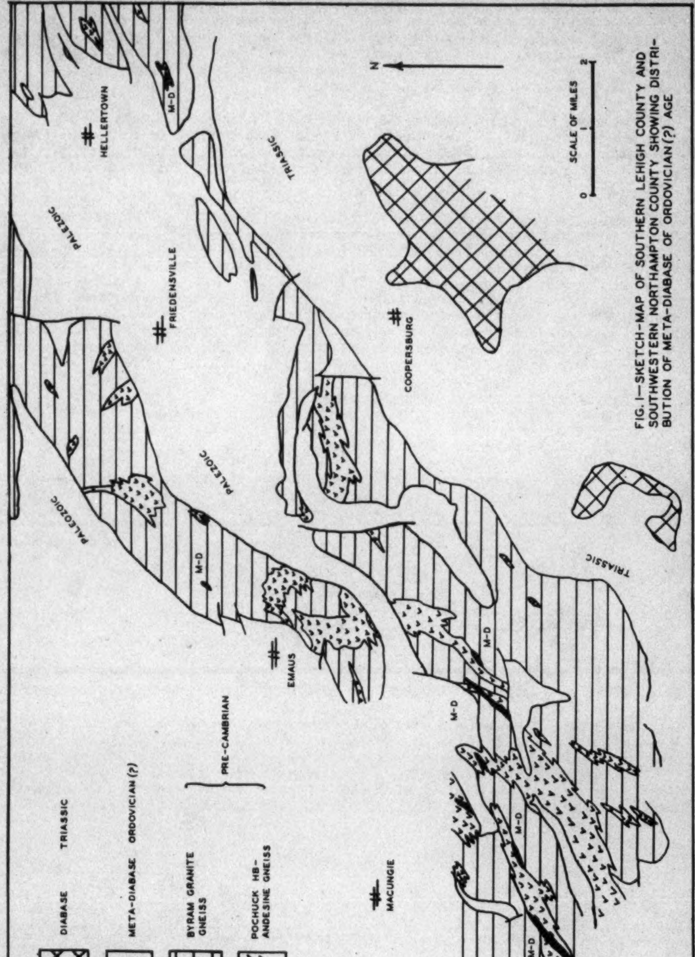
Basic rocks originally having diabasic, ophitic, and trachytoid structures but now altered to meta-diabases and meta-andesites of greenstone character appear in increasing abundance in the Pre-Cambrian belt of Eastern Pennsylvania in passing southwestward from the Delaware River. The problem connected with material discussed in this paper is chiefly one of age-relationships.


DIABASE
TRIASSIC
META-DIABASE
ORDOVICIAN (?)
M-D
BYRAM GRANITE GNEISS
POCHUCK HB-ANDESINE GNEISS
PRE-CAMBRIAN
HELLERTOWN
FRIEDENSVILLE
COOPERSBURG
EMAUS
MACUNGIE
PALEOZOIC
PALEOZOIC
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TRIASSIC
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SCALE OF MILES
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FIG. 1—SKETCH-MAP OF SOUTHERN LEHIGH COUNTY AND SOUTHWESTERN NORTHAMPTON COUNTY SHOWING DISTRIBUTION OF META-DIABASE OF ORDOVICIAN(?) AGE

Other basic rocks in the region include the Pochuck gneiss of Pre-Cambrian age which typically is a hornblende andesine gneiss of medium to coarse-grained texture having gneisose or granulose structure, and the Triassic diabase that occurs with the Triassic sedimentary rocks just southeast of the Pre-Cambrian belt.

The meta-diabases and meta-andesites (Fig. 1) occur in small isolated spots in the southern part of Northampton County and in more elongated areas in Lehigh County and Berks County to the southwest. Everywhere the basic rocks are found they show considerable alteration to a greenstone-type of material, which in the hand specimen is dense and hard but nevertheless shows evidence of the alteration of both feldspar and the ferromagnesian minerals. Hand specimens show a variation from dense almost flint-like rocks,which are extremely fine-grained, to medium-grained meta-diabasic rocks. In thin section, all types show primary augite and andesine or andesine-labradorite and secondary alteration to epidote, chlorite, sericite, saussurite, and magnetite. In many specimens, quartz and pyrite have been introduced.

The structures shown under the microscope include a trachytoid arrangement of labradorite laths in a fine-grained groundmass of augite, magnetite, and andesine-labradorite, flow-structure due to the parallel arrangement of andesine-labradorite laths and the more common diabasic and ophitic structures.

The field-occurrences are scattered and the material is traced chiefly by means of large rounded blocks at the surface so that the structural relations with the Pre-Cambrian formations are not known. It is assumed, however, that the greenstone has been intruded into the Pre-Cambrian as it does not possess the metamorphic structures present in these latter rocks and is therefore probably of later age.

Rocks of this type have long been recognized in the Pre-Cambrian belt of Eastern Pennsylvania. In Berks County in the area north of Boyertown and extending into the southern part of Lehigh County, altered diabasic rocks were recognized and described [see 1 of references at end of paper] in 1917, when they were considered to be Pre-Cambrian in age. More recently [2] one dike of this material has been indicated as Triassic in age. In the absence of any conclusive evidence regarding the age of these rocks, it seems desirable to sum up the similarities and differences existing between them and the Pre-Cambrian Pochuck gneiss and the Triassic diabase. With this thought in mind, the relations of the greenstone in question to the other basic rocks are discussed below.

Comparison with the Pochuck gneiss--The greenstone, which may be called a meta-diabase or meta-andesite, is commonly associated with the Pochuck gneiss in the field and was at first thought to represent a facies of this formation. From the thin-section studies, however, it was found that the greenstone contains augite and andesine or andesine-labradorite (Fig. 2) while the Pochuck typically carries hornblende in addition to augite and andesine (Fig. 3). Furthermore, the greenstone is altered by hydrothermal processes to epidote, chlorite, sericite, and saussurite, whereas alteration of the Pochuck produces uralite and sericite, and, except locally, only small amounts of epidote and chlorite. It would seem reasonable, therefore, on the basis of different mineralogy, the different metamorphic structures, and the different alteration-products, to assume a different origin for these two rock-types. The most reasonable interpretation is, of course, that the greenstone is later than the Pre-Cambrian Pochuck gneiss, has been intruded into it, and has been hydrothermally altered only, whereas the older formation, whatever its original nature, has been subjected to complete recrystallization as the result of dynamic metamorphism and later has been only slightly altered by hydrothermal action.

Comparison with the Triassic diabase--Triassic diabase (Fig. 4) has been examined in a number of sections and has been found to show relatively unaltered feldspars and augite with little evidence of hydrothermal alteration. The quartz present in this rock is commonly in the form of micrographic intergrowths and does not contain blebs or irregular areas replacing the other minerals. The greenstone (meta-diabase and meta-andesite), however, as has been stated and as is shown (Figs. 3 and 5), is always altered by the breaking down of the feldspars to sericite and saussurite and the alteration of augite to chlorite and epidote. In several sections of the greenstone, rounded or irregular quartz-areas (Fig. 5) appear which very probably have been introduced by hydrothermal solutions which brought about the change to the greenstone. Skeletal magnetite crystals are abundant in the greenstone, and pyrite was found in many of the specimens.

With reference to the relative ages of the Triassic diabase and the greenstone, attention is called to the much cleaner, unaltered appearance of the Triassic rock as contrasted with the typically altered greenstone. Furthermore, it would seem that, if solutions following the

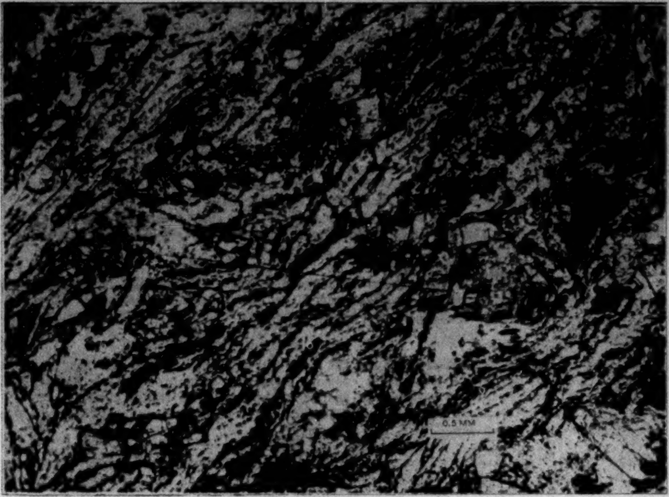

FIG. 2—META-DIABASE, ORDOVICIAN (?)

ANDESINE-LABRADORITE—TABULAR GRAINS ORIENTED BY FLOW ALONG LINE FROM UPPER RIGHT TO LOWER LEFT; AUGITE—ROUNDED GRAY KNOTS, LEFT AND RIGHT OF CENTER; QUARTZ (INTRODUCED)—IRREGULAR WHITE AREA BELOW AUGITE GRAIN AT RIGHT CENTER; SERICITE-SAUSSURITE—REPLACING FELDSPAR; EPIDOTE—FORMING FROM AUGITE

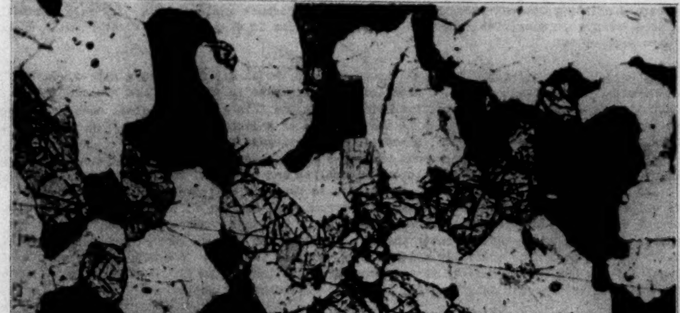

FIG. 3—POCHUCK GNEISS, PRE-CAMBRIAN

HORNBLENDE—DARK GRAY AND BLACK; AUGITE—LIGHTER GRAY WITH DISTINCT FRACTURES; ANDESINE—WHITE; APATITE—SMALL WHITE ELLIPTICAL INCLUSIONS

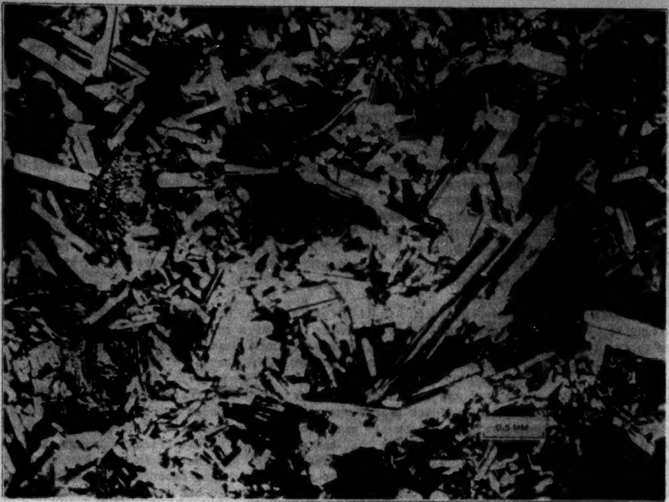

FIG. 4—DIABASE, TRIASSIC

LABRADORITE—TWINNED TABULAR GRAINS; AUGITE—DARK GRAY AND BLACK IRREGULAR AREAS; MICROGRAPHIC INTERGROWTH OF QUARTZ-ORTHOCLASE—LEFT CENTER SURROUNDED BY LABRADORITE; MAGNETITE—SMALLER BLACK GRAINS

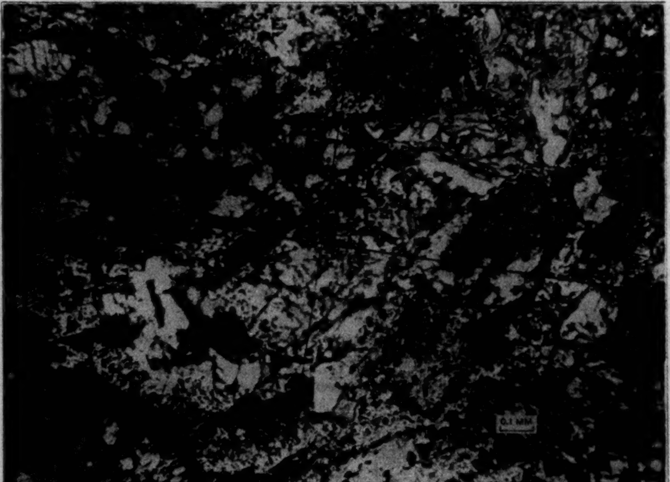

FIG. 5—META-DIABASE, ORDOVICIAN (?)

AUGITE—ROUNDED AREAS MIXED WITH MAGNETITE (BLACK) AT UPPER LEFT; ANDESINE-LABRADORITE—TABULAR GRAIN LOWER CENTER; QUARTZ (INTRODUCED)—WHITE AREAS, LOWER LEFT QUADRANT AND CUTTING CHLORITE AT UPPER RIGHT; CHLORITE—UPPER RIGHT WITH QUARTZ FORMED FROM AUGITE; EPIDOTE-SAUSSURITE SERICITE—FUZZY GROUND-MASS

Triassic invasion were capable of travelling along small dikes of basic material in the Pre-Cambrian causing the hydrothermal alteration shown by the specimens, there should be considerable evidence of some alteration in the larger diabase areas associated with the sandstones and shales of Triassic age. Such alteration, however, is lacking. For these reasons the greenstone has been regarded as being older than the Triassic diabase and is thought to have been hydrothermally altered before the emplacement of the Triassic diabase.

Comparison with Ordovician and post-Ordovician basic rocks--Specimens from Jonestown [3], where both diabase and basalt flows of Ordovician age occur, have been examined and have been found to show a similar type of hydrothermal alteration resulting in meta-basalts and meta-diabases similar in their mineralogy to the greenstones in question. The specimens from the Jonestown Area as well as those from Lehigh and Northampton counties show alteration of the feldspars to sericite and saussurite, and the breaking down of the augite. The resulting rocks have a green cast and are equally hard, dense materials typical of the partial hydrothermal alteration of fine-grained basic igneous rocks.

Basic dike rocks of post-Ordovician age [4] from Franklin, New Jersey, were examined and were found to be also quite similar. These specimens show more introduced granitic material but otherwise are like the greenstones in the Eastern Pennsylvania Highlands in showing abundant chlorite and epidote and intensive sericitization and saussuritization of the feldspars.

Conclusions--The structural and mineralogical evidence of the greater age of the Pochuck does not preclude the possibility of the greenstone being Pre-Cambrian but does indicate a much later age for the latter formation. Along the same lines of structural and mineralogical evidence, it is likewise not conclusively shown that the greenstone is not Triassic in age, but, as it consistently shows more general alteration, the indications are that it is somewhat older than the Triassic. The close similarity in structure and both primary and secondary mineralogic composition of the greenstone with other rocks of known Ordovician age has led to the tentative conclusion that the greenstone represented by the meta-diabase and meta-andesite should also be regarded as Ordovician in age. If this material is so regarded, we may then consider the scattered occurrences of basic intrusive material of Ordovician age as indicating a belt of weakness, in which fracturing occurred to a considerable depth and along which basic magmatic material rose toward the surface much as similar material cut the Triassic rocks at a later time by invading deep-reaching fractures which probably resulted from faulting.

Scattered occurrences of sericitized, epidotized, saussuritized, and silicified Pre-Cambrian rocks have long attested the abundance of hydrothermal solutions at some time in the past. The similar type of alteration of probable Ordovician basic rocks would indicate at least some of the solutions responsible for the alteration were late or post-Ordovician.

The lack of general hydrothermal alteration of the Triassic diabase would indicate that the period of hydrothermal action was pre-Triassic and probably occurred during Paleozoic time.

These relations add corroborative evidence to support previously published [5] views on the existence of an early or middle Paleozoic magmatic mass near the present Highlands area.

The writer wishes to express his appreciation to the National Research Council for a grant which made possible the thin sections used in connection with this study.

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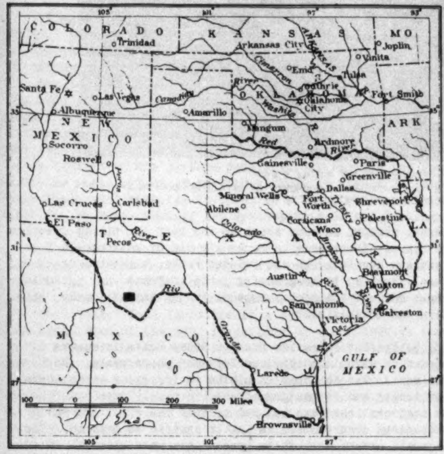
A SPHENOLITH IN THE TERLINGUA DISTRICT, TEXAS

Clyde P. Ross

(Published with the approval of the Director, U. S. Geological Survey)

Foreword--The Terlingua Quicksilver Mining District in the Big Bend of the Rio Grande in southwestern Texas (Fig. 1) contains numerous small intrusive masses of diverse shapes and compositions. Some of these have approximately the characteristics of sphenoliths as defined by C. Burckhardt (Géologie de la Sierra de Mazapil et Santa Rosa, Guide des excursions du X Congres Géologique International, Mexico, 1906, Part 26, pp. 33-36, 1906). They are roughly sill-like bodies which are irregularly wedge-shaped and appear to have made way for themselves in part by pushing aside the strata encountered. The intrusion of this character which forms Study Butte in the eastern part of the Terlingua District has been penetrated by extensive mine-workings, which give exceptional opportunity for study. The data on which the following description of the intrusion is based were obtained from studies of the accessible parts of the mine-workings coupled with plane-table mapping of the surface. The records of a number of diamond-drill holes gave information as to parts of the intrusive mass not yet reached in mining. The examination was made as part of an investigation of the Terlingua District carried out in 1934 for the United States Geological Survey with funds allotted by the Public Works Administration.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Fort Smith
Albuquerque
Amarillo
NEW MEXICO
Washita
ARK
Socorro
Mangum
Red River
Ardmore
Roswell
Gainesville
Paris
Greenville
Dallas
Mineral Wells
Fort Worth
Abilene
Shreveport
Las Cruces
Carlsbad
Trinity
Corsicana
Palestine
El Paso
Waco
LA
Pecos River
TEXAS
Colorado
Brazos
Pecos
Beaumont
Austin
Houston
Rio
Galveston
San Antonio
Victoria
MEXICO
Grande
GULF OF MEXICO
Laredo
100 0 100 200 300 Miles
Brownsville

FIG. 1—INDEX-MAP OF TEXAS, SHOWING LOCATION OF TERLINGUA DISTRICT

Geologic setting--The area is underlain by calcareous and argillaceous sedimentary rocks of Cretaceous age. The higher Cretaceous units contain volcanic material and appear in part to grade upward into, in part to be unconformably overlain by, an aggregate of tuffaceous and sedimentary beds and lava-flows believed to be mainly of Tertiary age. The Tertiary volcanic rocks may originally have covered much of the Terlingua District but are now absent from the vicinity of Study Butte. The stratigraphic succession is summarized in Table 1.

Table 1--Stratigraphic section, Terlingua District

Age		
Tertiary		Volcanics
Upper Cretaceous	Navarro	Tornillo clay
		Aguja formation
	Taylor	Terlingua clay
	Austin	Boquillas flags
	Eagle Ford	
Lower Cretaceous	Washita	Buda limestone
		Del Rio clay
	Fredericksburg	Devils River limestone

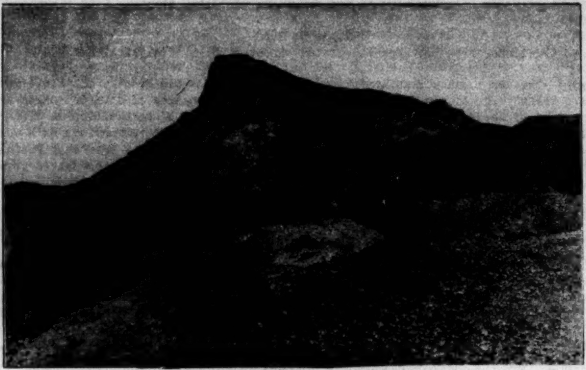

FIG. 2—STUDY BUTTE FROM EAST
(DARK ROCK OF CLIFF IS QUARTZ TRACHYTE; LOWER BOUNDARY OF INTRUSIVE MASS IS AT TOP OF TALUS SLOPE ON LEFT)

The small intrusions which are closely grouped in some areas in and near the Mining District include bosses, sills, sphenoliths, and dikes. The intrusive rocks are all of moderate to fine grain and more or less porphyritic. Most are keratophyres and related rocks, but there are some basaltic and andesitic masses. In general, here as in neighboring parts of Texas, the intrusive rocks are characterized by abundant soda. Many of the rocks, especially the basaltic ones, show conspicuously the effects of albitization and analcitization.

The rock of the sphenolith in Study Butte--The intrusive rock in Study Butte is quartz trachyte. It is a compact, cream-colored rock with inconspicuous feldspar phenocrysts. Dark minerals are rarely visible in hand specimens. The feldspar is albite in irregular laths which in the phenocrysts range up to two mm in length and in the groundmass are rarely more than 0.4 mm long. Quartz in interstitial grains composes less than ten per cent of the rock. Shreds of biotite, now bleached and altered, are sparsely distributed. A little apatite is present. The rock is generally fresh except that the small amount of biotite present has been altered. Close to the ore-deposits the feldspar shows incipient alteration, and a little calcite and pyrite have been introduced. A few of the feldspar crystals show faint traces of microcline textures and most of the grains, although free from visible products of alteration, are not evenly translucent. These facts suggest that the feldspar, whose indices are now nearly those of pure albite, may have originally been, at least in part, potassic.

Shape of the intrusion--The crest of Study Butte is elongated along an east-west line. The south side of the Butte has a cliff along its upper edge and to the north it slopes gently down to merge with the plain. These features are shown in Figure 2, except that the northern border of the Butte is beyond the limits of the view. As the Butte results from differential erosion, its shape reflects that of the igneous mass whose superior hardness has preserved the eminence. The intrusion is near the top of the Boquillas flags and the gentle back-slope of the Butte is composed of this rock. The sedimentary rock beneath the intrusion is largely concealed under the talus in the left-hand part of the photograph.

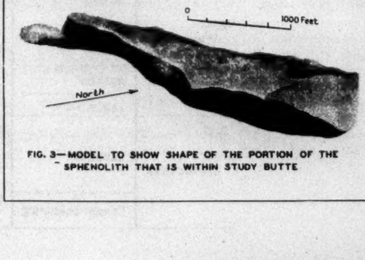

FIG. 3—MODEL TO SHOW SHAPE OF THE PORTION OF THE SPHENOLITH THAT IS WITHIN STUDY BUTTE

North of Study Butte the intrusive body is covered but from drill-cores and other data it appears to be an almost flat sill somewhat more than half a mile wide, from east to west, and about 500 feet thick in its thickest part, which is east of the middle. Where reached in mine-workings, the top of the sill accords very closely with the bedding in the overlying rock. The bottom is more irregular. Close to the northern border of the Butte the intrusive mass begins to rise. The argillaceous and somewhat calcareous flags on top are bent upward in essential conformity with the intrusion. Southward the thickness of the igneous mass narrows as it rises so that at the exposure in the cliff conspicuous in Figure 2 is less than 100 feet. Apparently the mass wedged out entirely a short distance south of the present cliff. The greatest uplift of the mass was near the middle of the edge of the wedge. The maximum rise here was fully 200 feet. It was sufficient to break across the upper contact of the Boquillas flags as the Terlingua clay, the next higher formation, is exposed at the base of the cliff in Figure 2, and is in contact with the lower side of the irregular igneous wedge in underground exposures. The clay is much disturbed along the contact and lies nearly flat a short distance to the south.

Figure 3 represents the shape of that portion of the intrusive mass that lies within Study Butte. It is a photograph of a model based on such accurate data that the true shape of the intrusive mass must correspond closely to that indicated in the Figure. A little less than half of the upper surface of the mass is now exposed as the surface for the full width shown in Figure 3. The southern edge, which forms the crest of the Butte (Fig. 2), has been eroded slightly and the edge of the lower surface of the intrusion is exposed at the base of the cliff shown in Figure 2. Mine-workings ramify through most of the part of the intrusive mass shown in Figure 3 and extend to the upturned under side in several places. The workings have a maximum depth of 250 feet below the collar of a shaft over 100 feet lower than the crest of the Butte. Diamond-drill holes from the surface pass entirely through the intrusive mass in several places, mostly near the north border of the block shown in Figure 3. More detailed description of the available data, with maps, is included in a report on the Terlingua Region as a whole now in preparation (C. P. Ross, Geology and ore-deposits of the Terlingua Region, Texas).

The mass tapers on the west to a pointed projection with blunt edges approximately as shown in the model. No data are available regarding the lower side of this projecting part. The narrowness of this projection, in a north-south direction, may be related to a fault which is exposed at the surface just east of the place where the mass, as reconstructed in Figure 3, resumes its full size. This fault trends a little west of north and brings Terlingua clay down against the north side of the west projection of the intrusive mass, whereas Boquillas flags lie on the north side of the mass for most of the rest of its extent. As the mine-workings here are inaccessible, the extent to which the fault may affect igneous rock was not learned. A wedge of baked clay is enclosed in the igneous rock in about the same longitude as the fault but nearer the south edge of the intrusion. This wedge, as now exposed at the surface, trends northeast, is about 125 feet long and generally less than five feet thick. It has an exposed vertical dimension of over 25 feet. It is hidden from view behind the high part of the front edge of the mass in Figure 3. The western part of the igneous mass presents steep edges on both its southern and northern sides. On the northern side the beds of Terlingua clay are baked and bent up sharply in a zone about 20 feet wide. The east end of the intrusive mass is not exposed either at the surface or in mine-workings and consequently cannot be shown on Figure 3.

The igneous rock is extensively and intricately jointed. In the interior the most prominent joints are vertical or steeply inclined. Below the northern border of the Butte the principal set of such joints trends about north 65° east, which corresponds to the trend of the principal set of joints in the sedimentary rocks of the region. To the southeast, in the thickest part of the wedge, the principal steep joints trend north to north 10° east. In both localities, but especially in the second-mentioned, there are numerous other joints of diverse trends. Close to the border of the under side of the wedge the joints are particularly irregular and discontinuous. Some movement has taken place along certain of the joints, but the displacement is very slight. In surface-exposures the igneous rock is everywhere sheeted parallel to the upper contact. On the higher slopes of the Butte the sedimentary rock has been eroded away, but the sheeted zone serves to show that the contact originally lay but little above the present ground-surface. On the north side of the west point of the intrusive mass, where the sedimentary beds are bent steeply against the steep face of the intrusion, the sheeted zone in the igneous rock is correspondingly steep. The texture of the igneous rock is somewhat finer near the borders than in the interior of the mass, but the sheeted zone is a much more definite feature of the rock in the vicinity of the contact.

Mode of intrusion--The sphenolith above described and the numerous similar intrusions in the region are genetically related to the period of volcanism in which the volcanics overlying the Tornillo clay were erupted. Some of the intrusions that are petrographically like that in Study Butte cut lava-flows so they must have come to place rather late in the period of volcanism. On the basis of more or less rough estimates of the thickness of the different stratigraphic units involved, it appears that the sphenolith in Study Butte cannot have been much more than a mile below the surface at the time of intrusion. If it was intruded when only a fraction of the full thickness of the volcanics covered the site, the depth may have been less than 4000 feet.

The magma entered the beds near the top of the Boquillas flags some distance north of the site of Study Butte through a conduit not now revealed. It moved southward perhaps as much as a mile along the beds without seriously disturbing those above it. Then it began to rise, tilting the beds above it and cutting across those in front. Apparently the effort thus required served as an effective check on the progress of the magma. As soon as the magma started to rise, it began to narrow down into a wedge-shape and in a short distance progress of the wedge ceased entirely.

The cause of the upward deflection of the originally sill-shaped mass is not clear. The intrusion was moving at an angle nearly normal to the strike of major joints of the regional joint system. Possibly previous crustal adjustments had produced enough movement on some of the joint planes on the site of Study Butte to cause the magma to change its course. The wedge of baked clay, elongated parallel to the principal joints and frozen into the igneous rock now in the Butte, suggests such an explanation. Movement along the fault near the west end of the Butte may have started prior to intrusion as the igneous rock on the down throw side cuts stratigraphically higher beds than those on the upthrow side. This fault, however, trends so nearly in the same direction as that followed by the magma that it could not have acted as a deflecting agent. Doubtless the rocks bordering this fault, the fracture marked by the clay wedge, and other fractures in the sedimentary rocks suffered displacement as the wedge of magma pushed upward. The rock on the front, or under, side is so deformed as to prove that the magma exerted force on it, but this rock is so soft and yielding that the force exerted need not have been great. Minor adjustments took place after the magma had consolidated, but these produced insignificant displacements.

One of the most significant features of this intrusion is the evidence afforded by it that sufficient force was exerted through the agency of the advancing magma to deform the rock that was being intruded by it. The amount of deformation was small, but so was the magma-body. If the same kind of action had been able to continue, the mass would have lost all resemblance to a sill. It would have become a sharply transgressive intrusion bordered by a zone of deformed strata. Several of the small bosses in the general vicinity of Terlingua have this character and may well have had such an origin. The effects traceable in small masses of this sort may have a bearing on problems related to batholithic masses so large that similarly complete information cannot be obtained.

U. S. Geological Survey,
Washington, D. C.

MODE OF IGNEOUS INTRUSION IN LA PLATA MOUNTAINS, COLORADO

Edwin B. Eckel

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The La Plata Mountains, in southwestern Colorado, have long been known as an example of a mountain group of the laccolithic type, although it has been recognized that the igneous geology was much more complex than that of typical laccoliths. A restudy of the ore-deposits of the District, now in progress, has thrown new light on the mode of intrusion of the igneous rocks (E. B. Eckel, Resurvey of the geology and ore-deposits of the La Plata Mining District, Colorado, Proc. Colorado Sci. Soc., v. 13, No. 9, pp. 508-546, 1936).

The Mountains, which include parts of La Plata and Montezuma Counties, are 8 to 18 miles northwest of Durango and occupy an oval area 10 to 15 miles in diameter. The altitude ranges from about 8000 to 13,225 feet above sea-level.

The La Plata Mountains have been carved from a domal uplift of sedimentary rocks that was intruded by numerous stocks, dikes, and sills during Tertiary time. The sedimentary rocks range from Pennsylvanian to Upper Cretaceous in age and are in large part typical red beds that are made up of limy shales and mudstones, arkosic grits, and conglomerates. The section contains two thick sandstones and a few beds of limestone.

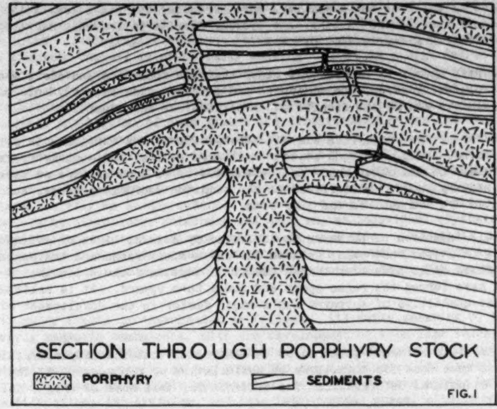

FIG. 1

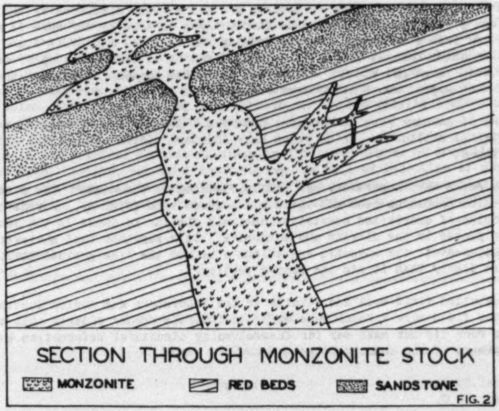

FIG. 2

FIG. 1—SCHEMATIC SECTION THROUGH PORPHYRY STOCK AND ASSOCIATED SILLS
(BEDS NEAR STOCK WALLS HAVE BEEN TURNED NEARLY ON EDGE AND SILLS HAVE FORCED THE ROCKS APART AND DOMED THEM UPWARD)
FIG. 2—SCHEMATIC SECTION THROUGH MONZONITE STOCK—VERTICAL SCALE ROUGHLY 2000 FEET
(EXISTING STRUCTURES ARE NOT DISTURBED AND STOCK NARROWS WHERE IT PASSES THROUGH THICK BED OF SANDSTONE)

The igneous rocks vary widely in composition and in form. Only two general types are considered here--porphyritic and nonporphyritic diorite and monzonite. Porphyry, most of which is intermediate between diorite and monzonite in composition, is more abundant than any other rock-type. The porphyry occurs as stocks, sills, and dikes. All of these forms are closely related, and there is little doubt that all are nearly contemporaneous and that the stocks represent the major channels through which the magmas moved that formed the sills and dikes.

The nonporphyritic monzonite is essentially confined to one long, irregular stock. It is a medium-fine, equigranular, gray to pinkish gray rock. One large stock of diorite is exposed in the central part of the dome and a smaller, more irregular diorite stock, which is surrounded by many dikes, occurs east of the center. The typical diorite is somewhat darker-gray than the monzonite, and is finer-grained in most places.

The porphyries appear to be somewhat older than the monzonite and diorite and to be cut by them. In some places, however, the monzonite and diorite grade directly into porphyry. No evidence of the relative age of the diorite and monzonite has been found.

The intrusion of the porphyries was not accompanied by any considerable metamorphism of the country rocks, since sills are found between unaltered beds of sedimentary rocks. The monzonite and diorite stocks, on the other hand, are surrounded by an area of more or less intensely metamorphosed sedimentary rocks. Silicification has been the dominant process, but contact metamorphic silicates are abundant in the limy beds.

The forcible injection of porphyry is indicated by several lines of evidence. Figure 1 illustrates the relations that exist between the sedimentary rocks and the porphyry masses. The beds near the stock-walls have been turned nearly on edge, and the sills that worked out from the main stock have forced the rocks apart and domed them upward. It is believed that the intrusion of great quantities of porphyry was a major factor in the development of the La Plata Dome.

Much of the field-evidence gathered so far indicates that the nonporphyritic diorite and the monzonite masses made room for themselves by assimilation or replacement of the country rock rather than by structural deformation. The evidence for this mode of origin follows.

As shown in Figure 2, existing structures are not visibly disturbed by the monzonite or diorite. In one place, near the monzonite stock, there is a large exposure of rocks that appear to be sedimentary from a distance, as both bedding and regional structure stand out plainly. Close inspection shows that at least half of this area is actually made up of monzonite in the form of dikes both large and minute, sills, and irregular masses. In places the sedimentary rocks contain what appear to be introduced feldspars.

Inclusions of country rock are nowhere numerous. All of the inclusions seen, however, retain their original attitudes. In no place have adjacent blocks with widely differing strikes or dips been found.

Siliceous rocks were apparently not easily digested by the magma. The stocks narrow as they pass through thick sandstone beds and again widen above them (Fig. 2). Furthermore, rounded, water-worn pebbles of quartz and quartzite, entirely similar to those in the intruded conglomerates, occur in places in the diorite and monzonite. This suggests that whatever may have been the mode of emplacement, the magmatic emanations attacked the fine-grained matrix of the conglomerates more freely than it did the quartz pebbles.

Further detailed field-work and studies in the laboratory may modify conclusions in some details, but the field-work already done seems to indicate rather clearly that the stocks of nonporphyritic rock did not make way for themselves by structural deformation but by assimilation or replacement of the country rocks.

U. S. Geological Survey,
Washington, D. C.

THE PROBLEM OF THE CHELMSFORD, MASSACHUSETTS, GRANITE

L. W. Currier

(Abstract)

(Published with the approval of the Director, U. S. Geological Survey)

The Chelmsford granite is quarried in and around Oak Hill, about six miles west of Lowell, Massachusetts. The granite-area is about eight miles long and one to three miles wide, and its longer dimension has a northeast bearing which is parallel with the regional axis of foliation in the country rock. The writer favors a hypothesis that much of the granite represents granitization of biotite schist under hydro-magmatic invasion, and under stress that was insufficient to deform or distort the preexisting country rock-structures to any marked degree. Banding of the granite is due chiefly to variable amounts of biotite. The bands are thin and remarkably uniform. The banding, attitudes of schist inclusions, and distribution of the entire mass con-

form to the regional structural elements. Lit-par-lit injection-bands are not clearly discernible although many of the light-colored bands are doubtless of such origin. The absence of flow-schlieren is noted. Petrographic evidence shows a remarkable amount of metasomatic fabric. Undoubted primary granitic texture is practically wanting. There is a high degree of orientation of biotite, muscovite, and groups of small mosaic quartz-grains. The contacts of inclusions with adjacent granite-bands are very irregular and interpenetrative, and granitic material also penetrates intricately along schistosity planes within the inclusions. Large irregular feldspar porphyroblasts and strings of such grains are distributed through the inclusions, generally with decreasing concentration toward the centers. Pegmatite and quartz veins, some of which carry much tourmaline, are abundant in some of the quarries. Crystallization zoning of feldspars is very rare. Feldspars are of three generations: (1) Early polysynthetically twinned porphyroblasts and irregular groundmass grains of oligoclase or albite-oligoclase; (2) microcline and orthoclase, chiefly as porphyroblasts, and in part replacing the earlier plagioclase; and (3) albite and albite-oligoclase, untwinned and mottled, as individual crystals, streaks, patches, and porphyroblasts, replacing microcline, quartz, and mica. Incomplete twinning, corrosion-contacts, optical anomalies, inclusions of minerals, pseudo-perthitic and myrmekitic grains are among the diagnostic petrographic features that contribute to the theory of replacement.

A sequence of major events is interpreted as follows: (1) Early shearing of biotite schist and invasion by early magmatic emanations, with the development of soda-lime feldspar (oligoclase, and others); (2) general mild stress accompanied by thorough penetration by alkalic solutions, with the development of microcline and muscovite porphyroblasts; (3) later, probably continuing, invasion and permeation by sodic hydrothermal solutions forming albite metasomes, and causing general albitization; (4) cracking, and late hydrothermal stage, with development of epidote, quartz, apatite, zircon, titanite, chlorite, and subordinate feldspar. Tourmaline-bearing veins are of late deposition, but the exact position in this sequence is not established. Questions are raised regarding (1) the extent to which such a replacement-granite may approach a normal granite in general appearance, through the gradual elimination of relic banding, and (2) the disposal of replaced bases such as magnesia, iron, lime, and titanium, which might account for the appearance of chlorite, biotite, and hornblende schists in areas of so-called regional "dynamic" metamorphism, these bases having been carried far into overlying country rocks, and deposited at lower temperatures under various degrees of stress.

Field-studies in east-central Vermont disclose an incipient degree of granitization among schists of the chlorite, biotite, and hornblende facies, as well as injection of sodic granitic materials, and the writer suggests the possibility that this regional metamorphism may have been partly or largely effected by processes similar to the granitization processes of the Chelmsford, Massachusetts, area.

U. S. Geological Survey,
Washington, D. C.

THE HYDRATED CALCIUM SILICATES

E. P. Flint and Lansing S. Wells

(Abstract)

The hydrated-calcium silicates are of particular geological interest as typical minerals formed by hydrothermal reactions at contact-zones of different mineral species. They are also of technical significance as compounds which may be formed in the steam-treatment of Portland cement and pozzolanic materials and in the manufacture of sand-lime brick. To ascertain which of the hydrated-calcium silicates reported in the literature are distinct minerals, X-ray diffraction-patterns have been made on samples obtained mostly from the United States National Museum. Patterns were also made on the following anhydrous calcium silicates: Wollastonite, pseudo-wollastonite, beta- and gamma- di-calcium silicates, tricalcium disilicate, and tricalcium silicate. The other phase of the investigation now in progress, and on which this paper is a preliminary report, is an attempt to synthesize some of the hydrated-calcium silicates by hydrothermal methods.

Results of the X-ray study are as follows:

The minerals, gyrolite [$4CaO.6SiO_2.5(H, Na, K)_2O$], centrallasite [$4CaO.7SiO_2.3H_2O$], and truscottite [$4(Ca, Mg)O.7SiO_2.3H_2O$] were found to be very closely related, if not identical.

All of the lines in the pattern of centrallasite are present in the same positions in the pattern of truscottite, which has, however, some additional lines. Gyrolite has lines found in truscottite but not in centrallasite, as well as lines common to all three.

Of the hydrated-monocalcium silicates, riversideite [$2CaO.2SiO_2.3H_2O$] has a pattern which is distinctive except for some relationship with wollastonite. The positions of several of the more intense lines in riversideite appear to be identical with some of the more intense lines in wollastonite. Crestmoreite [$4CaO.4SiO_2.7H_2O$] and xonotlite [$5CaO.5SiO_2.H_2O$] have characteristic and distinctive patterns.

Foshagite obtained from the United States National Museum gave complete identity of pattern with riversideite from the United States National Museum. A sample labeled foshagite from Ward's Natural Science Establishment proved to be made up of two minerals, one having the pattern of riversideite, the other that of hillebrandite.

The following remaining minerals gave characteristic and distinctive patterns: Okenite [$2CaO.4SiO_2.3H_2O$]; afwillite [$3CaO.2SiO_2.3H_2O$]; and hillebrandite [$2CaO.SiO_2.H_2O$].

A study of the hydrothermal synthesis of some of these minerals yielded the following results:

Precipitated hydrated-calcium silicate with CaO/SiO_2 ratio = 1.0 on treatment with water in a bomb for six weeks at 215° C was 50 per cent crystallized to tufts and bundles of fibrous crystals; indices 1.545, 1.553; parallel extinction, positive elongation. No satisfactory X-ray pattern of this material has been obtained.

Amorphous hydrated-monocalcium silicate treated with water for periods of from four to 14 days at 300° C to 395° ± 10° C (200 atm) crystallized completely to material having the chemical composition, optical properties, and X-ray pattern of xonotlite. Above 395° ± 10° C wollastonite was obtained.

Pseudo-wollastonite at 500° C, 400 atm, for three weeks, was 50 to 60 per cent converted to wollastonite.

Anhydrous tricalcium disilicate at 500° C, 380 atm, for two weeks, was 90 per cent converted to a product consisting of small needle and rod-shaped crystals with indices 1.605, 1.615, and having a composition corresponding to $3CaO.2SiO_2.0.5H_2O$. The X-ray pattern was different from those of the other hydrated or anhydrous-calcium silicates. Precipitated hydrated-calcium silicate with CaO/SiO_2 ratio = 1.5 treated at 325° C and at 350° C for 12 days was partially crystallized and gave the pattern of xonotlite.

Beta-$2CaO.SiO_2$ treated with water at 150° C for seven days was completely converted to pseudo-hillebrandite [$2CaO.SiO_2.H_2O$], $\alpha = 1.614 \pm 0.002$, $\beta = 1.620 \pm 0.002$, $\gamma = 1.633 \pm 0.002$. This compound was also formed from beta-$2CaO.SiO_2$ and water at 110° C and 200° C. A mixture of lime and silica-gel in equimolar amounts treated with water at 150° C for six days gave pseudo-hillebrandite and silica-gel. Pseudo-hillebrandite treated with water at 250° C for two weeks was unchanged; treated at 450° C (400 atm) for one week it gave a product of unchanged crystal form but having maximum and minimum indices about 0.03 higher than the corresponding indices of pseudo-hillebrandite. This material gave a distinctive X-ray pattern and its composition corresponded to the formula $2CaO.SiO_2.2/3H_2O$.

One gram of tricalcium silicate treated with 500 cc of water for nine years at room-temperature was completely converted to a hydrated material of composition $1.32CaO:1.00SiO_2:1.65H_2O$, probably a mixture of hydrous-calcium silicates. The X-ray pattern of this material was different from that of calcite or any of the hydrous or anhydrous calcium silicates.

National Bureau of Standards,
Washington, D. C.

THE VOLCANIC DOME OF SANTA MARIA, GUATEMALA

E. G. Zies

(Abstract)

A historical review of the development of the dome of Santa Maria was presented. Dome-building began in 1922 and continued actively for a period of three years. The dome attained

during this time a height of approximately 2500 feet. Since 1925 its height has remained fairly constant but its diameter is increasing by accretions brought about by intermittent activity in various parts of the edifice. This activity is occasionally accompanied by eruptions.

When visited in 1935, the fumaroles were very active and the maximum recorded temperature of the escaping gases (mostly steam) was over 400° C. The presence of hydrofluoric acid was determined by analysis of the incrustations.

Attention was directed to the desirability of using this intensely active area as a field-laboratory for studying the various aspects of dome-building. Emphasis was laid on the necessity of determining the present dimensions of the dome for purposes of comparison with its dimensions in the future.

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CRYSTALLIZATION OF MELTS OF NEPHELINE AND ALBITE WITH FAYALITE

N. L. Bowen

(Abstract)

A thermal study of the system $NaAlSiO_4$-FeO-SiO_2 shows that the crystalline phases formed are cristobalite, tridymite, albite, fayalite, nepheline, carnegieite, hercynite, and wüstite. There are two ternary eutectics, one between tridymite, albite, and fayalite (980 ± 10° C) which may be regarded as a simplified fayalite-rhyolite, and the other between nepheline, albite, and fayalite (990 ± 10° C) which may be regarded as a simplified fayalite phonolite. The results are considered in their relation to the origin of natural phonolites, trachytes, and rhyolites carrying fayalite.

Geophysical Laboratory,
Carnegie Institution of Washington,
Washington, D. C.

TEMPERATURES IN A SINKING XENOLITH

T. S. Lovering

The manuscript for this paper was not submitted.

University of Michigan,
Ann Arbor, Michigan

MODE OF EMPLACEMENT OF THE POST-PALEOZOIC INTRUSIVES OF THE TUCSON QUADRANGLE, ARIZONA

B. N. Moore

The manuscript for this paper was not submitted.

U. S. Geological Survey,
Washington, D. C.

THE VOLCANIC SEQUENCE IN THE BULL VALLEY REGION IN SOUTHWESTERN UTAH

F. G. Wells

The manuscript for this paper was not submitted.

U. S. Geological Survey,
Washington, D. C.

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NATIONAL RESEARCH COUNCIL

TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION

EIGHTEENTH ANNUAL MEETING
APRIL 28, 29, 30, 1937
WASHINGTON, D. C.

REGIONAL MEETING
JUNE 21 TO 26, 1937
DENVER, COLORADO

PART II

REPORTS AND PAPERS
SECTION OF HYDROLOGY
AND
SOUTH CONTINENTAL DIVIDE SNOW-SURVEY CONFERENCE

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
JULY, 1937

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Eighteenth Annual Meeting

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REPORT OF THE COMMITTEE ON SNOW, 1936-37

J. E. Church, Chairman

Organization and Personnel

Since snow, rainfall, and glaciers constitute the raw material of much of the Section of Hydrology, and runoff and floods are their results, the Committee on Snow has sought membership from all of these overlapping fields to attain breadth of understanding and the spirit of cooperation. To share the benefits of international cooperation, representatives from Canada have been requested to accept membership. Because of the present pioneer stage of snow-surveying and the Committee's opportunity to foster its development, representation has also been sought for various watersheds where stream-development is increasing the public interest in snow.

In the following list of members of the Committee the sphere or locality of special interest of each member is represented in parenthesis. The asterisk (*) after names indicates cooperating members.

J. E. Church, Chairman--Meteorologist, Nevada Agricultural Experiment Station, Reno, Nevada (Snow)
E. S. Cullings, Vice-Chairman--Secretary of Black River Regulating District, Watertown, New York (Water-supply forecasting; Eastern States)
Carl Elges, Secretary--Assistant Meteorologist, Nevada Agricultural Experiment Station, Reno, Nevada (Snow-surveying)
W. W. McLaughlin--Chief, United States Division of Irrigation, Berkeley, California (Water-supply forecasting; Western States)
Joseph Kittredge, Jr.--Professor of Forestry, University of California, Berkeley, California (Evaporation of snow; snow-conservation)
L. K. Sherman--Chairman, Section of Hydrology, American Geophysical Union, Chicago, Illinois, and Consulting Engineer (Rainfall)
François E. Matthes--Geologist, United States Geological Survey, Washington, D. C. (High mountain-snow; glaciers)
H. K. Barrows--Professor of Hydraulic Engineering, Massachusetts Institute of Technology, Boston, Massachusetts (Water-power; flood-control)
Gerard H. Matthes--Chairman, Mississippi River Commission, Vicksburg, Mississippi (Floods)
Lacey V. Murrow*--Director of Highways, State of Washington, Olympia, Washington (Snow-removal)
Howard T. Barnes*--Professor of Physics (Emeritus), McGill University, Montreal, Canada (Snow- and ice-engineering)
Salvatore Pagliuca--Observer, Blue Hill Meteorological Observatory, Milton, Massachusetts (Forecasting snow and sleet for highways)
S. P. Fergusson--Research Associate, Blue Hill Observatory, Milton, Massachusetts (Instruments)
Bestor Robinson*--Chairman, Winter Sports, Sierra Club, Oakland, California (Snow-sports)
Dr. Henry Ives Baldwin*--Assistant Forester for Forest Research, New Hampshire Forestry and Recreation Department, Hillsboro, New Hampshire (Physics of snow for sports)
Robert G. Stone--Librarian, Blue Hill Observatory, and Editor, Bulletin of American Meteorological Society, Milton, Massachusetts (Bibliography)

Regional representatives

- Paul L. Bean--Agent and Engineer, Union Water Power Company, Lewiston, Maine (New England)
- G. A. Hathaway--Senior Engineer, Corps of Engineers, United States Army, Washington, D. C. (Missouri River Basin)
- E. B. Debler*--Hydraulic Engineer, United States Reclamation Service, Denver, Colorado (Colorado River Basin)
- George D. Clyde--Dean, College of Engineering, Utah State Agricultural College, Logan, Utah (Eastern Great Basin; runoff)
- H. P. Boardman--Professor of Civil Engineering, University of Nevada, and Chairman, Nevada Cooperative Snow-Surveys, Reno, Nevada (Great Western Basin; normals)
- Harlowe M. Stafford--Water and Snow Supervisor, State Department of Public Works, Sacramento, California (Pacific Coast)
- J. H. Ryan--Assistant State Engineer, In Charge Oregon State Snow Survey, Salem, Oregon (Lower Columbia Basin)

Regional representatives--Continued

E. H. Collins*--Assistant Engineer, Washington Water Power Company, Spokane, Washington (Upper Columbia Basin)

Eric Hinton--Engineer, International Power and Paper Company of Newfoundland, Deer Lake, Newfoundland (Newfoundland)

M. Balls*--Hydraulic Engineer, Shawingan Power Company, Montreal, Canada (Eastern Canada)

O. H. Hoover*--Engineer-in-Charge, Dominion Water Power and Hydrometric Bureau, Calgary, Alberta, Canada (Alberta; Bow Basin)

R. C. Farrow--Hydraulic Engineer, Water Rights Branch, Victoria, British Columbia, Canada (British Columbia; especially Canadian Columbia Basin)

W. A. Lamb--District Engineer, Water Resources Branch, United States Geological Survey, Helena, Montana (Forecasting international streams; St. Mary River)

William H. Hobbs--Professor of Geology (Emeritus), University of Michigan, Ann Arbor, Michigan (International Commission of Snow; arctic)

Laurence M. Gould--Professor of Geology and Geography, Carleton College, Northfield, Minnesota (Antarctic)

Since meetings of the Section of Hydrology are far distant and committees constitute the chief point of contact between members, the Committee on Snow has been made large. Three new fields of interest have been formally added: (1) Forecasting snow and sleet for highway traffic; (2) snow-removal from highways; (3) snow-sports. The field of bibliography, always an essential part of activity of a committee, has been further expanded with a special member to represent it.

Because of the organization of the Federal-State Cooperative Snow-Survey System for the Western States, its Director, W. W. McLaughlin, has been made a representative on the Committee for that area. However, the pioneering nature of snow-surveying makes desirable the retention also of the representatives of Western local areas.

Progress

As compared with the unusual developments of last year, progress during the present year has become mainly a matter of perfecting routine and beginning preparations for the meeting of the International Association of Scientific Hydrology at Washington, D. C., in 1939.

Extension of the Federal-State Cooperative Snow-Survey System and the initiation of the numerous research-projects outlined in last year's annual report await increase in Congressional appropriation. The total appropriation thus far has been only $15,000 annually. However, the Department of Agriculture and the National Resources Committee are recommending improvement in basic hydrologic data to keep pace with present interest in the economic use and control of water (see "Deficiencies in basic hydrologic data," September, 1936, by the National Resources Committee).

As exceptions to the above quietude should be mentioned the steady growth of snow-surveying systems in New York, New England, and British Columbia. From the latter Province has come a fundamental research-project on the relation of snowfall to runoff. To should be added the active development of the International Commission of Snow.

Regional and project reports

Closely paralleling the reversal in relative temperature this past winter in the East and the West, the snow-cover at low elevations was thin in the former region and heavy in the latter. So effective was the cold in the West in turning usual rain to snow that the snow-cover was relatively and, on the western slope of the Sierra Nevada, actually quantitatively heavier at lower elevations than at high. The result should be a diminution of winter-flow and a corresponding increase in spring-flow.

The result of the relative high temperature in the East was unprecedented midwinter floods and the appearance of icebergs on the Atlantic steamer-lanes in early February.

The inversion of the water-content of the snow in the West must bring a reversal to the expectation of the public that too often estimates the runoff for summer from the snow actually under foot. In such seasons as this the method of "altitude-areas" finds demonstration of its need and emergency value. Monthly snow-surveys promptly corrected mis-impressions.

The nation-wide snow-survey and forecast of water-resources reveal the following general condition:

New England (Paul L. Bean)

The snow-cover has been greatest along the Maine-Canadian Boundary and tapers off rapidly to the south and east.

We classify the year as wet and very satisfactory for power-purposes. This winter has been remarkable in that the cold front has been absent from November 1936 to February 15, 1937.

We are maintaining about 600 miles of snow-traverse with regular readings of depth of snow, water-content of the snow, observations on ice-cover beneath the snow, frost in the ground, and ground-water levels at a few stations. We are determining water-content of the snow from sea-level to 3600-foot elevations. We maintain one station at 1500-foot elevation, where daily readings of water-content of the snow are made.

I am of the opinion that long-range weather-forecasting should be studied more intensely by the Weather Bureau and that more funds should be made available for that Bureau, also that ground-water studies should be extended. We are working on this latter problem here and extending our observations as fast as funds will permit. We have nothing to report at this time.

The Maine Development Commission at Augusta, Maine, publishes much data on snow-sports and the State Highway Commission at Augusta reports on snow-removal.

Eastern Canada (M. Balls)

Apparently very little progress has been made in the practical application of snow-surveys to problems of runoff in Eastern Canada. In the very few watersheds where snow-surveys have been carried on it has not yet been possible to establish anything approaching a definite relationship between the water-content of snow-cover, as measured in March, and the runoff during the ensuing months of April, May, and June. Usually this water-content amounts to about 20 per cent of the annual precipitation, whereas the runoff during April, May, and June averages about 56 per cent of the total runoff for the year.

Some of the wide divergence in seasonal results may be relative to the departure from the normal effect of: (1) The volume of water in the ground immediately prior to the freeze-up; (2) the condition of the ground, whether frozen or not, under snow-cover; (3) occasional rains and thaws in winter, causing a decrease in snow-cover and temporary rise in stream-flow; and (4) the intensity of the thaw in spring, particularly in combination with item (2).

No doubt these, and possibly other, factors have an important bearing upon the relationship between water-content of snow-cover and runoff in spring.

In the St. Maurice River watershed, snow-surveys have been carried out over a period of ten years and, while the results have not been conclusive, they have at least been helpful in providing an indication of the volume of runoff in spring which might be expected under normal conditions. For this reason, and in the hope that further study of the variable factors may eventually lead to more reliable forecasts, the snow-surveys will be continued.

New York (Arthur W. Harrington)

The original Adirondack snow-surveys have now grown into the New York Cooperative Snow-Survey, with Arthur W. Harrington, District Engineer, United States Geological Survey (Water Resources Branch), Albany, N. Y., as Chairman of Snow-Survey Committee. Although the average precipitation for the month was only slightly below normal, there was slight accumulation of snow on March 1.

International, Montana-Alberta (W. T. McFarlane)

The results of our International Snow-Survey on the headquarters of the St. Mary River at Many Glacier, Mont., indicate a runoff slightly less than 1936, which was an average year. Our first snow-survey was made at Lake Louise the end of March. The indications there point to a low runoff.

British Columbia (R. C. Farrow)

The Comptroller of Water Rights is developing a complete system of snow-survey courses on upper Columbia and the Kootenay to forecast stream-flow for power in British Columbia and cooperate with American snow-survey system downstream. Six new courses will be added next June.

An unusually hot spell of abnormal duration last May and June created flood-conditions on the Fraser, Kootenay, and Columbia rivers in British Columbia, causing considerable damage. The most serious lasting result was the consequent early and rapid runoff on the Kootenay River, which left the West Kootenay Power Co. very short of water throughout last summer and this winter at its plants below Nelson, B. C. Their average requirement for maximum operation is 11000 cfs, and, while the Kootenay generally falls below this for the low winter months, it has never fallen so low nor remained so low for such a large part of any year since the Company started operating--reaching a record low flow of 3500 cfs. The resulting drop in power-output found its reflection in a curtailment of the operations of the Big Trail Smelter.

If Kootenay Lake could be used for storage, its balancing effect would be of great benefit to users on the Kootenay River and would also be beneficial to the Columbia River itself. But unfortunately international complications have prohibited Kootenay Lake being used for storage.

The writer has made no study so far of snow-surveys in relation to flood-prediction, but desires to do so in the particular case of the Fraser as soon as time and opportunity occur. It is my private opinion that we shall soon be considering a snow-survey network for Fraser

River drainage, and once the system is initiated, we shall, I know, be expected to make an effort at flood-prediction.

The Powell River Company, Limited, large pulp and paper manufacturers at Powell River, British Columbia, about 70 miles up the coast from Vancouver, desire to set up a snow-survey system over their watershed and have requested our help and guidance. They want their system to be standardized with ours. I shall be going over there in April to get them started, and shall probably help them lay out a few of their courses.

It is going to be a difficult area for forecasting, like all our coastal basins, as the transition from rain in winter to snow is rapid as one goes inland from the sea. Numerous courses and zoning will be necessary, and precipitation during runoff will probably be a disturbing factor in many years. It will, nevertheless, be an interesting basin to experiment in, and the Company, I think, is prepared to spend whatever is necessary to assure success.

Oregon (J. H. Ryan)

In general the snow which has melted in the lower country has not caused any appreciable rise in the streams. For example, there was a total snowfall of 56 inches at Antone, Wheeler County, which is at elevation of approximately 3700 feet. The snow has all melted except the larger drifts without an increase showing in the creeks, the soil having retained all of the moisture.

We had somewhat the same situation last year and our forecasts were high due to the fact that we did not properly evaluate the effect of the dry soil on the runoff. This year we have an aggravated situation and we will attempt to make the proper allowances. I will greatly appreciate any information which may be available regarding the influence of a dry fall and early winter on the following summer's runoff.

Last year the Federal Department of Agricultural Engineering undertook to collect some information regarding the penetration of moisture on the range-lands and expected to study it in connection with the flow of springs in summer, but may delay progress for some time.

California (Harold Conkling)

Although the Legislature of 1935 reestablished the participation of the State in the snow-survey work, the appropriation made was but half that previously expended for this purpose. This has kept us hard-pushed to maintain our program already established and has prevented any experimental or research work, necessary and desirable though such work may be.

The California program has gained much this year through the beginning of active participation by the United States Forest Service. Although in past years the Service has allowed us the use of its ranger-cabins as headquarters for our winter snow-surveys, it has never heretofore actually participated in this work. This year, however, through the intervention of Mr. McLaughlin, Chief of the Bureau of Irrigation, the Forest Service has taken an active interest and through its enthusiastic cooperation we have been able to establish and survey some 16 much desired new snow-courses at strategic locations throughout the Sierra.

As a result of seven continuous years of snow-survey records we are beginning to get results from our forecasting that are satisfactory and convincing as to the real value of snow-surveys in forecasting runoff in spring from the mountains. At 22 stations in 12 of the main drainage-basins of the western slope of the Sierra for which forecasts of April-July runoff were made in April 1936, the divergence between forecasts and the actual was less than 10 per cent in 17 cases, between 10 and 20 per cent in three cases, and only exceeded 20 per cent in two cases. Such results are gratifying.

Conservation

The California Agricultural Experiment Station is conducting a long-time project on the effect of forests in conserving snow. This project is located on the western slope of the Sierra near the elevation of maximum rainfall and under conditions of relatively high humidity.

Professor Joseph Kittredge, Jr., Division of Forestry in the University of California, leader of the project, reports the last year's findings as follows:

"The records of accumulation, evolution, and melting of the snow-cover under different forest-conditions between elevations of 5000 and 6300 feet in the Stanislaus River drainage are being continued for the fourth winter. Wide differences exist between types in the maximum accumulation which is usually found at a station in an opening between the trees. The range in February, 1936, was from 30 inches water-equivalent in the red-fir type to eight inches in the ponderosa-pine type. Dates of disappearance of the last snow show a correspondingly wide range--in the ponderosa-pine on April 10 and not until May 20 in the red-fir.

"Evaporation from the snow under these conditions is notably low as a result of the counterbalancing effect of condensation. A gain by condensation was recorded in 72 per cent of the night-records and a loss by evaporation in 83 per cent of the day-records. The net excess of evaporation over condensation per 24 hours averaged only 0.0014-inch water-equivalent. During the period in April and May when most of the water from the snow goes into the soil, the rate of melting varied from 0.7-inch to 2.0-inch water-equivalent per 24 hours. This is comparable with the rate in moderate to heavy rains and probably does not exceed the infiltration-capacity of these forested soils."

The relative effect of timber in conserving snow against melting by wind has been observed on Mount Washington in connection with the flood of April 1936 by John Dick of Mount Washington Observatory. Details are given by Dr. Henry I. Baldwin and Dr. Charles F. Brooks in "Forests and floods in New Hampshire." Their conclusion is: "If the State of New Hampshire had been covered with a dense stand of spruce, hemlock, fir, and pine, the flood of March, 1936, would have been merely the flood of the decade instead of the great flood of the century."

Floods

The floods of 1936 in the East are undergoing analysis according to the report of Dr. H. K. Barrows, which follows:

"Of course, you are aware of the fact that we had extremely unusual flood-conditions here in New England about a year ago (in March 1936), due in part to excessive rainfall, but also to a large extent to melting snow. The District Engineer of the Geological Survey, H. B. Kinnison, is preparing a comprehensive report on the whole subject which I think will be of much value. As I understand it, this will include quite complete data in regard to snow, precipitation, and runoff, with flood hydrographs in many cases, and should prove of great value in the study of hydrology.

"I note you suggest that it might be well to hold a meeting here in the East at some future time in the way of a snow-survey conference. I think this would be an excellent plan. While our problems are somewhat different from yours, I think that much of interest might be developed by such a meeting."

Gerard H. Matthes, Chairman of the Mississippi River Commission, is also studying counteracting factors in flood-control as over-storage and frozen channels.

The unprecedented floods of 1937 received their main impetus from the lowlands rather than the mountains and can be ascribed mainly to congested rain. As expressed by J. B. Kincer, Chief of the Division of Climate and Crops of the United States Weather Bureau: "The record-breaking rains over the flood-areas have brought about four-months' normal precipitation in less than a month, but not enough to erase the long-time deficiency." Herein lie data for study of possible retarding effect of drought on floods.

Winter sports

Snow-sports have been given a feeling of security through the recent publication of Seligman's "Snow-structure and ski-fields," which has become a "bible to cross-country skiers, especially with reference to avalanche-hazards." They have also received direction and impetus both in the East and the West through timely broadcasts of snow- and weather-conditions.

In the West, Bestor Robinson, its Chairman, reports that "the Winter-Sports Committee of the Sierra Club has been collecting data and intends to continue to do so concerning length of snow-season, avalanche-hazards, and the conditions on varying exposures which form the types of snow that skiers desire for the practice of their sport.

"In connection with the Sierra Crest ski-trails which are to be constructed this coming summer, we plan to establish a system of avalanche-reports, in order to give proper warning as to the location of dangerous slopes and the conditions which produce this danger. Our group contemplated that this work would be entirely empirical and would rest without an attempt to repeat on Seligman's scientific works."

Since Seligman's "Snow-structure" is preliminary to further investigation, it is hoped that some observations can be made in America to supplement studies of the physics of snow in Switzerland and the Arctic. The study of the upper layers will be especially valuable in winter sports. Dr. Henry L. Baldwin will pursue this work in the Eastern States. Bestor Robinson is author of an article on "Equipment and technique for camping on snow" and Dr. Baldwin has written on "Ski-trail cover: Can the season be prolonged?"

The geographical extent of winter sports is even broader than at first supposed. Robert G. Stone writes: "They have quite a bit of snow in western North Carolina--more than we have at Boston--and this winter more snow fell there than in this section. A small college at Banner's Elk, North Carolina, about 4000 feet elevation, gives a course in skiing to its students! Mt. Mitchell has about 80 to 90 inches of snow per year--I think there are some winter-sports possibilities down there for sure!"

Equipment

Improvement of snow-sampling equipment has now entered into its minor stages. Anoiding or aluminating treatment has provided duralumin with a non-oxidizing surface. A sectional duralumin-staff for the spring-balance has been perfected. By the addition of a steel section of approximately one inch to the duralumin tubing a durable foundation has been provided for threads by which the cutter can be screwed into place. This will permit easy removal of the cutter in the field. However, experiments are still under way to determine the possibility of using the expansion-shrinkage method of attachment and that of soldering.

Prolonged observations must be made of the tendency of the duralumin sampler and staff to clog in the snow under certain conditions of snow-cover and temperature. Simultaneous tests will be made of both steel and duralumin to determine whether the latter is specially at fault.

James C. Marr, Associate Irrigation Engineer of the United States Division of Irrigation, is designing an electric weighing-scale for the snow-sampler. Its initial handicaps are greater weight, difficulty of providing a ready support in the field, and the possibility of the freezing of the batteries under prolonged exposure to low temperature.

Arctic

Scientific attention is now being concentrated on the Arctic. The Soviet Union has discovered new islands by means of ice-breakers and is establishing a floating meteorological observatory on the ice near the North Pole.

Professor Hans W$^{\underline{\text{son}}}$ Ahlmann of Sweden in his glacier-studies in Iceland has discovered the continuous evolution of new snow into firn and thence into glacial ice.

Dr. Fritz Loewe, now of Australia, and Max Demorest of Princeton University, have presented elaborate prospectuses for proposed expeditions to the Inland Ice of Greenland.

The Federal-State Cooperative Snow-Surveys

Two new developments have occurred in Federal cooperation in snow-surveys. The United States Weather Bureau now publishes in its "Climatological data and snowfall bulletins" the results of all Federal-State Cooperative Snow-Surveys. Furthermore, its River and Flood Division is planning to organize in the Eastern States a system of cooperative snow-surveys similar to that now conducted by the United States Bureau of Agricultural Engineering in the West. Thus the Federal-State System will soon embrace all snow-fed watersheds of the United States. Canada is cooperating closely on all international streams.

Publicity

Publicity is taking the practical form of reports known as "Snow-surveys and seasonal forecast of stream-flow." Utah provides "Water-supply forecasts" and the United States Bureau of Agricultural Engineering issues "Irrigation-water forecasts." The distinction lies in the type and breadth of service.

Radio broadcasts are frequent. The United States Division of Irrigation conducts a series from San Francisco on Western States snow-surveys. The Humboldt National Forest of Nevada and the states of Nevada, Utah, and Idaho have issued local broadcasts of water-supplies and human-interest tales of ideals and methods. The Chairman has broadcasted and written on "International snow."

Research

The noteworthy feature of the regional reports are the various problems arising in connection with forecasting stream-flow. A special advisory committee on hydrologic data of the National Water Resources Committee is now formulating preliminary proposals for projects in hydrologic research, including precipitation and snow-surveying.

International Commission of Snow

The earlier tendency toward variant geographic groups and isolation from the International Union has now vanished. The Baltic Conference has formally centered its snow- and ice-interests in the International Commission and Peter Stakle, Chairman of its Board of Curators, has been elected Secretary of the Commission. The Soviet Union, leader in the study of ice, has wholeheartedly joined in the work of the International Union and has refused to sponsor an International Congress of Cryology until the present pioneer work in snow and ice warrants.

An urgent presentation was made by Dr. Antoni Dobrowolski of the ideal desirability of reorganizing the Commissions of Snow and Glaciers into an Association of Cryology coordinate with the Associations of Meteorology and Scientific Hydrology, but the question was deferred for final decision to the meeting at Washington in 1939.

Discussion was also had regarding the desirability of combining these two commissions into a single Commission of Snow and Ice. Because of hesitation on the part of some members to destroying the identity of the old and highly specialized Commission of Glaciers, no organic union was effected. However, the Commission of Snow was granted the entire field of snow and ice except such part as might be taken over by the Commission of Glaciers, and the latter requested that the two commissions keep very close together.

Thus practically the Commission of Snow was granted the breadth and freedom of an Association of Snow and Ice without withdrawing from the parent Association of Scientific Hydrology much of the data essential to its existence. Its officers also represent its three large fields: Dr. J. E. Church, President, snow; Dr. Antoni B. Dobrowolski, Vice-President, ice; Peter Stakle, Secretary, cold.

The Commission's three problems for investigation and report in 1939 are: (1) The permeability of snow with respect to water and the capacity of the snow to retain water; (2) influence of snow and ice on the flow of streams with reference to the condition of the ground, as to whether it is normal or frozen, and to condensation; (3) compilation of snow-maps of all countries.

However, these three problems are merely formal. The informal activities embrace: (a) Interchange of information on all problems of snow and ice, including especially the exchange of reports and published material; and (b) active pursuit of problems throughout the interval between meetings. These activities will be strengthened by an Annual Letter to all members containing news from all countries and a bibliography of all publications as suggestions for mutual exchange of material.

Already two essential requests have been received: (1) Explanation of the cause of the abnormal and seemingly persistent low minimum-flow in the Punjab, India; and (2) review of a new method of selecting sites for snow-survey courses on the upper Columbia River in British Columbia. Thus geographic isolation is compensated by an advisory center, and the work of the Commission is vitalized by its broad contacts, a fact that brought high praise from Secretary Dienert of the International Association.

A grant of 7000 Swiss francs or approximately $1600 is under consideration for printing the proceedings of the Edinburgh Meeting of the Commission.

Summaries of leading publications

Under the new plan of summarizing the more important publications of the year, the following Carnegie Institution of Washington publications have been selected because of their fundamental value and despite the lapse of time since their printing. These summaries have been written by J. A. Folse, Curator, Department of Power, Museum of Science and Industry, Chicago, who prepared the uncompleted studies of Dean Hayford for publication and extended his work.

"Effects of winds and of barometric pressures on the Great Lakes," by John F. Hayford, Carnegie Institution of Washington, Publication 317, 1922--This volume should be of interest to hydrologists, engineers, and physicists, not only because it represents an outstanding contribution to existing geophysical knowledge which has definite practical applications of considerable importance, but because of the unusual methods employed in the analysis.

The volume represents a partial report on a much broader investigation which had for its ultimate object a better formulation of the laws governing the amount of stream-flow than the engineering profession then had. This broad investigation was begun in the summer of 1911 under the direction of the late Dr. John F. Hayford, then Dean of the School of Engineering of Northwestern University and formerly Chief of the Computing Division of the United States Coast and Geodetic Survey, and was financed by the Carnegie Institution of Washington. The investigation was carried on continuously, except for two years of the Great War, from 1911 to the time of Dr. Hayford's death in 1925. The work accomplished after 1922 was published in 1929 as Publication No. 400 of the Carnegie Institution of Washington entitled "A new method of estimating stream-flow based upon a new evaporation-formula" by J. A. Folse.

The usual methods of analysis used in this research are stated on pages 6 to 8 of Publication 317, and can not be repeated here for want of space. These methods are applicable to a great many problems in engineering, "pure" science, economics, etc., and should be of interest to those concerned.

The results of the research reported upon in Publication 317 are stated on pages 8 and 9. These are:

"(1) Reasonably accurate numerical expressions have been obtained for the effects of barometric pressures on the elevation of the water-surface at the five stations, Buffalo, Cleveland, Milwaukee, Mackinaw, and Harbor Beach, on Lake Erie and on Lake Michigan-Huron. With these expressions, one may, from the distribution of barometric pressures ordinarily shown on the forecast-maps of the Weather Bureau, compute the disturbances in elevation of the water-surface thereby produced at the stations named.

"(2) The general method has been developed by which such a numerical expression for the barometric effect at any station on any body of water may be derived from observations of the water-elevation at that station and the forecast-maps for the same period.

"(3) A general expression, including the necessary numerical constant, has been obtained for the effect of winds, of any given velocity and direction, in producing a disturbance of elevation of the water-surface at any given station, on any body of water, anywhere in the world. The data required in regard to the station and the body of water are such as are ordinarily shown on good charts, namely, the depths of the water at all points, the location of the shoreline, and the location of the station.

"(4) Four of the prevailing seiches, or free oscillations under the influence of inertia, on Lake Erie and Lake Michigan-Huron have been isolated. Their periods and probable methods of oscillation have been shown. The relation between these seiches and the uncertainties in daily mean elevations of the water-surface at gage-stations has been discerned. The appreciation of this relation aids decidedly in obtaining accurate determinations of the daily mean elevation of the mean surface of each lake.

"(5) The accuracy with which the elevation of the mean surface of any one of the Great Lakes may be determined for any given day has been decidedly increased. On Lake Erie the elevation of the mean surface of the Lake may now be determined as accurately from one day of observation at Buffalo as it was formerly possible to fix it from 16 days of observation at that station. Similarly, the elevation of the mean surface of Lake Michigan-Huron may now be determined as accurately from one day of observation at Mackinaw as it was formerly possible to determine it from six days of observation at that station. When one determines the fluctuation of elevation of the mean surface of a lake he thereby determines the fluctuation in the total water-content of the lake.

"(6) The relations of the new knowledge indicated in (1) to (5) to four outstanding problems have become evident. The four problems are: (a) The problem of regulating the elevations of the water-surface of each of the Great Lakes--and the rates of flow through the connecting streams, so as to secure the greatest aggregate benefits to navigation, power, development, and sanitation. (b) The problem of determining the laws of evaporation from large free-water surfaces such as the surface of the Great Lakes. (c) The problem of correcting the observed elevations of the water-surface at a tide-gage in such a manner as to remove the disturbances due to winds and fluctuating barometric pressures and thereby to secure a more accurate determination of mean sea-level than could otherwise be obtained from said observations. (d) The problem of determining the direction and rate of the tilting, which is believed to be in progress, of the land underlying and immediately surrounding the Great Lakes."

"A new method of estimating stream-flow, based upon a new evaporation formula" by J. A. Folse, Carnegie Institution of Washington, Publication 400, 1929--This volume reports upon the second phase of an investigation of the laws governing stream-flow, which was begun in 1911 under the direction of the late Dr. John F. Hayford, and financed by the Carnegie Institution of Washington. A report (Publication 317) was issued in 1922 covering the progress made from 1911 to 1922. Publication 400 covers the work accomplished from 1922 to 1926, inclusive.

The outcome of the second part of this research-project (as reported upon in Publication 400) may be briefly stated as follows:

(1) An evaporation-formula has been derived, based upon over 700 observations independently on each of two of the Great Lakes, Michigan-Huron and Superior. This formula enables one to estimate the daily rate of evaporation from any free, open surface of water (such as from the surface of a lake, reservoir, or river) anywhere in the world, in terms of the meteorological elements of air-temperature, vapor-pressure, and wind-velocity as ordinarily observed at the standard United States Weather Bureau stations.

(2) An estimate has been made of the constant part of the runoff into each of lakes Michigan-Huron and Superior from their respective land drainage-areas, and certain general knowledge with reference to the variable parts of the runoff in each case has been obtained.

(3) As a direct sequel to the results already published in Publication 317, and as a necessary precursor of item (1), the following two items of knowledge have been derived: (a) A reasonably accurate numerical expression has been obtained for the effects of barometric pressures on the elevation of the water-surface at the Marquette Station on Lake Superior. With this expression one may compute, from the distribution of the barometric pressure ordinarily shown on the forecast-maps of the Weather Bureau, the disturbances in elevation of the water-surface thereby produced at Marquette. (b) The numerical constants (the Σ's) in the general formula for wind-effects stated as equation (69), page 63, Publication 317, have been derived for the Marquette Station on Lake Superior. These constants enable one to compute the hourly or daily effect of a wind of any velocity and direction upon the elevation of the water-surface at Marquette, Michigan.

(4) The relationship of the new knowledge gained in (1) and (2) to various important problems in science and engineering has become increasingly evident. Some of these problems are: (a) The problem of estimating the evaporation from the surface of each of the Great Lakes as a basis for more accurate estimates of the hydrological phase of the problem of regulating the surfaces of the lakes by controlling works in their connecting channels, and the use of this

available knowledge of the daily evaporation in such regulation after the controlling works are constructed. (b) The problem of estimating the evaporation from other large open-surfaces of water, such as the surfaces of reservoirs, lakes, and rivers, in the design of controlling works for power, irrigation, navigation, and sanitation. (c) The problem of estimating the evaporation from large land-surfaces as a basis for estimating the runoff from such surfaces for use in various engineering and scientific problems.

(5) Approximate quantitative expressions of the fundamental laws of flow of two streams, A and B, Wagon Wheel Gap, Colorado, have been derived. These numerical expressions enable one to compute the daily flow of these two streams from the observed weather-elements of wind-velocity, air-temperature, vapor-pressure, rainfall- and snow-gagings with a reasonably good degree of approximation.

(6) The general method has been developed by which such expressions can be derived for any stream anywhere in the eastern two-thirds of the United States where the annual rainfall is 20 inches or more from parallel observations of stream-flow, as measured by the United States Geological Survey, or otherwise, and from the meteorological elements as observed by the Weather Bureau.

(7) The relation of the new knowledge stated in (5) and (6) to three important problems has become evident. The three problems are: (a) The problem of increasing the length of record of flow of a stream, the hydrograph, as a basis for greater accuracy in the design of works for power, irrigation, sanitation, and navigation. (b) The problem of forecasting the flow of a stream as a basis for increasing the economy of operation of hydro-electric power-plants; and to reduce the damage from floods. (c) The problem of determining the effect of forest cover on the runoff from watersheds.

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Appreciation

The Chairman desires to mention again the generosity of the Nevada Agricultural Experiment Station which was not only the parent of Western snow-surveying but has acted as patron both of the American Committee on Snow and the International Commission of Snow. Without its cooperation and financial support, many of the activities of the Committee would have been impossible. To the Experiment Station should now be added the United States Division of Irrigation, which not only shared in the expense of the trip to study Western watersheds last summer but encouraged in every way possible the trip to Edinburgh and the watersheds of western Europe.

Nevada Agricultural Experiment Station,
Reno, Nevada

REPORT OF COMMITTEE ON GLACIERS, 1936-37

François E. Matthes, Chairman

The Committee was enlarged during the past year by one more member, Prof. J. E. Church of Reno, Nevada, Chairman of the Committee on Snow, who agreed to serve on it while the Chairman of the Committee on Glaciers in turn accepted membership on the Committee on Snow. Thus the two Committees, whose spheres of work are in some respects intimately related, have been brought into closer touch with each other.

Although the Committee on Glaciers has assembled considerable data on different lines of glaciologic research during the past few years, it seems best to confine this report, like the preceding ones, to a record of the variations--advance or recession--of glaciers in the continental United States and Alaska, and to reserve the other data for presentation later, in separate papers. The variations of glaciers here reported are for the 12-month period from the autumn of 1935 to the autumn of 1936.

The Committee takes this occasion to express to its collaborators in the field its sense of indebtedness to them, and its deep appreciation of their faithful and wholly disinterested efforts in securing, annually, reliable data on the variations of American and Alaskan glaciers. Few glaciers, it is realized, are readily accessible, and visits to the fronts of the great majority of them, for the purpose of making measurements, usually involve the surmounting of physical obstacles, and often the enduring of discomfort and hardship. Without the volunteer services of its collaborators, it would be impossible for the Committee to carry on its program of systematic recording of variations of glaciers from year to year.

Glaciers of Mount Baker

The Mountaineers of Seattle, Washington, in the autumn of 1936, revisited the Easton Glacier, the recession of which they measured for the first time in 1935, and extended their observations to the Coleman Glacier (formerly known as Roosevelt Glacier), which is one of the largest ice-bodies on Mount Baker, situated on the northwest flank of the Peak, almost diametrically opposite the Easton Glacier. Thus one more important glacier has been added to the list of those in the Pacific Northwest that are being measured systematically from year to year. The matter is of peculiar interest to hydrologists, glaciologists, and climatologists, because of all the glaciers in the continental United States those in the Pacific Northwest, although situated in the region of heaviest snow-precipitation, are at present receding at the most rapid rates; among them the glaciers on Mount Baker easily lead all others in rapidity of recession. Herbert V. Strandberg, under whose leadership the measurements are being made, submits the following report:

Easton Glacier, on September 19, 1936, had receded 170 feet from its position in 1935. Its recession during the preceding year was 190 feet; hence the total shortening suffered by this ice-stream since the establishment of the base-line at its front in 1934 is 360 feet.

That this remarkable recession is not merely of the nature of a brief spurt, but is representative of the mean rate that has prevailed for at least a quarter of a century, is to be inferred from the position of the glacier's terminus shown on the topographic map of Mount Baker, made by the United States Geological Survey in 1908; also from a photograph taken by Henry Enberg in 1910. Although necessarily lacking in exactness, these early topographic and photographic records are nevertheless valuable in that they are consistent in their indications of the approximate extent of the ice-mass in the years in which they were made. The map shows the terminus at a point some 4900 feet in advance of the position in 1936. The mean annual recession for the 28-year period therefore was about 175 feet. The photograph shows the terminus about 4170 feet in advance of the position in 1936, indicating a mean annual recession for the past 26 years of about 160 feet.

These recession-figures are more than twice as large as those of the Nisqually Glacier, on Mount Rainier, whose rapid and steady recession has lately attracted the attention of glaciologists in Europe as well as in the United States. The Nisqually, it is true, receded as much as 155 feet in 1934, and exceeded 100 feet twice before in the 18-year period during which systematic measurements of its recession have been made, but its mean rate for that period is only 71 feet per year. The contrast is the more significant as Mount Baker is situated 134 miles farther north than Mount Rainier and much nearer the Pacific Coast (30 miles east of Bellingham Bay). The Easton and the Nisqually both have southerly exposures and in that respect are directly comparable.

Coleman Glacier appears to be receding at a much slower rate than Easton Glacier, but that fact is not surprising considering that Coleman Glacier has a northwesterly exposure and Easton Glacier has a south-southeasterly exposure. As yet, no direct measurement of recession has been made on the Coleman Glacier, but from an excellent photograph (the "Mount Baker Cartogram") taken by Mr. Sandison in 1910 from a lookout-point near the town of Glacier, it has been possible to determine the location of the terminus in that year with a probable error of ± 100 feet; actual measurements from that point up to the present position of the terminus, made on September 6, 1936, show a recession of 2228 feet. The mean annual rate of recession for the 26-year period therefore appears to have been about 86 feet. Even this rate, it will be seen, exceeds the mean rate of recession of the Nisqually Glacier.

Glaciers of Mount Rainier

From C. Frank Brockman, Park Naturalist of Mount Rainier National Park, a comprehensive report was received covering for each of the six glaciers that are being measured annually by him the complete recession-record, as far back as it extends. As these records reveal the general trend of the recession of these glaciers, and as they have not been brought together elsewhere in convenient form for study and comparison, it seems desirable here to present them in full.

Nisqually Glacier on south side of Mount Rainier

Year	Recession in feet	Year	Recession in feet
1857-1885[a]	760	1926-1927	43
1885-1892[a]	140	1927-1928	89
1892-1918[a]	1310	1928-1929	52
1918-1919	59	1929-1930	118
1919-1920	46	1930-1931	49
1920-1921	106	1931-1932	50
1921-1922	67	1932-1933	44
1922-1923	44	1933-1934	155
1923-1924	83	1934-1935	54
1924-1925	73	1935-1936	65
1925-1926	86		

[a] From authentic historical sources; annual measurements by the National Park Service began in 1918.

From the above tabulation it appears that the total recession during the 79-year period, 1857 to 1936, was 3493 feet. The mean annual recession for that period, therefore, was 44 feet. However, the mean rate appears to be constantly increasing. From 1857 to 1892 it was 26 feet per year; from 1892 to 1918 it was 50 feet per year; from 1918 to 1936 it was 71 feet.

South Tahoma Glacier (on southwest side of Peak--terminus confluent with a lobe of the Tahoma Glacier).

Year	Point A Recession in feet	Point B Recession in feet
1931-1932	37	..
1932-1933	13	..
1933-1934	73	(Reference-point established)
1934-1935	61	42
1935-1936	66	79
Totals and means	250 50	121 60.5

Carbon Glacier (on northwest side of Peak--terminus shaded by canyon-walls).

Year	Recession in feet
1932-1933	12
1933-1934	29
1934-1935	24
1935-1936	67
Total and mean	132 33

Emmons Glacier (on northeast side of the Peak--the largest glacier in the continental United States, about six miles long) has offered considerable difficulty in measurements of recession, because its broad and ill-defined terminus is heavily mantled with moranic material. Mr. Brockman's plan has been to measure from an established base-line to the point of effluence of White River, where the ice is clearly exposed, but as the stream shifts its position from year to year, these measurements do not always give results that are representative for the terminus as a whole. Supplementary measurements to the approximate location of the stream's point of effluence of the year before, though inexact, probably give a more truly representative measure of the glacier's recession. The results of both sets of measurements are given below.

Year	Recession in feet at Point of effluence of White River	Approximate previous point of effluence
1930-1931	142	..
1931-1932	2.5	19
1932-1933	48.5	32
1933-1934	2.5	132
1934-1935	67	30
1935-1936	193	100
Totals and means	455.5 76	313 63

Stevens Glacier (on south-southeast side of Peak--a secondary glacier occupying a broad bench between two primary glaciers).

Year	Recession in feet
1934-1935	(Reference-point lost)
1935-1936	146

Paradise Glacier (now little more than a stagnant lobe of the Stevens Glacier) has had measurements made from three reference-points opposite its broad front.

Year	Point A Recession in feet	Point B Recession in feet	Point C Recession in feet
1932-1933	7	5.0	7
1933-1934		34.5	24
1934-1935	72	23.5	34
1935-1936		60.0	
Totals and means	79 19.7	123.0 30.7	65 16.2

Resurvey of Nisqually Glacier

In addition to the foregoing recession-data from the National Park Service, a preliminary report has been received from G. L. Parker, District Engineer of the Water Resources Branch, United States Geological Survey, on the resurvey of the lower Nisqually Glacier in September, 1936. This resurvey was carried out in pursuance of a cooperative agreement entered into by the Geological Survey and the City of Tacoma in 1931, calling for the periodic remapping of the lower course of the Nisqually at intervals of five years.

The first survey was executed in October, 1931, by the planetable-and-stadia method, and resulted in a detailed map of the glacier's surface for a distance of two miles up from the terminus. This map was drawn on a scale of 1:4800 and with a contour-interval of 20 feet. The resurvey, in 1936, was executed by the same method and yielded a second map drawn on the same scale and with the same contour-interval. Accordingly there are now available for direct comparison two maps of essentially equal accuracy.

There is available, further, the topographic map of Mount Rainier National Park, which was made by the United States Geological Survey in 1910 and 1911; but as that map shows the Nisqually Glacier on a scale of 1:48,000 (ten times as small as the special surveys mentioned above) and with a contour-interval of 100 feet, it necessarily is too generalized to afford a satisfactory basis for comparison. Nevertheless, it serves to show, within the limitations of its scale, the dimensions and configuration of the ice-mass at the time of the topographic survey (August, 1910).

The final computations of loss of volume of the ice-mass, based on comparisons of the three maps, were not yet available when this report was being prepared, but a few outstanding facts can be stated at this time:

(1) The terminus in 1931 lay 1325 feet back of the point which it occupied in 1910.

(2) The ice in 1910 was 210 feet deep at the point where the terminus lay in 1931.

(3) From 1910 to 1931 the glacier lost from 80 to 120 feet in depth over a stretch of, roughly, 4000 feet. Farther up the losses by ablation were insignificant.

(4) The terminus in 1936 lay 368 feet back of the point which it occupied in 1931.

(5) The ice in 1931 was about 120 feet deep at the point where the terminus lay in 1936.

(6) From 1931 to 1936 the glacier lost from 40 to 80 feet in depth over a stretch of 3500 feet. Farther up the losses by ablation were insignificant over a stretch of about 1000 feet. Still farther up conditions were reversed and the ice in 1936 was 20 to 40 feet deeper than in 1931. This swelling of the glacier in the upper portion of the mapped area remains to be accounted for.

Glaciers of Mount Hood

The following data are taken from a detailed and illustrated report by Kenneth N. Phillips, Chairman of the Research Committee of the Mazamas, of Portland, Oregon:

Eliot Glacier, when visited on September 20, 1936, had receded 20 feet from the position which its front occupied on September 15, 1935. Its recession since October 19, 1935, however, was only eight feet. The rate of forward movement of the ice at the terminus, as determined with two cryocinemeters, on September 20, 1936, averaged 0.77 inch per day.

The following estimates were made of the discharge of Eliot Creek, just below its point of effluence: August 2, 1936, at 18^h, 40 second-feet; September 20, 1936, at 8^h, 8 second-feet; September 20, 1936, at 15^h 30^m, 30 second-feet.

Coe Glacier's position of terminus was not determined. Discharge of stream on August 2, at 16^h 15^m, was estimated at 30 second-feet.

Ladd Glacier, on August 2, was five feet in advance of its position on October 20, 1935. However, it seemed probable that by October 20, 1936, its terminus would recede practically to the position it occupied on October 20, 1935. It may therefore be regarded as essentially stationary. Discharge of stream on August 2, at 14^h, was estimated at 25 second-feet.

White River Glacier, on August 9, 1936, was for the first time triangulated from a chained base-line, and the position of its front, thus determined, was compared with that shown on the topographic map made in 1907 by A. H. Sylvester of the United States Geological Survey, and with its position in 1901 as estimated by Dr. Harry Fielding Reid from a known observation-point. If, as Mr. Phillips states, all observations could be relied upon as exact determinations, the glacier must have advanced about 160 feet from 1901 to 1907, and it must have receded 2000 feet from 1907 to 1936. However, the advance from 1901 to 1907 can not be regarded as definitely attested, and it seems best, therefore, to state that the recession from 1901 to 1936 was 1840 feet, assuming Reid's estimate to be fairly accurate. Cryocinemeter-readings at the terminus of White River Glacier, continued for a period of four hours and thirteen minutes, on October 11, 1936, indicated a forward movement of the ice at the rate of 1.74 inches per day.

Glaciers of Mount Shasta

From Oliver Kehrlein, Chairman of the Committee on Glacier Studies of the Sierra Club, the following data were received on the status of the glaciers on Mount Shasta.

Hotlum Glacier, the largest glacier on the Peak, situated on its northeast side, in September, 1936, showed no appreciable recession since September, 1935, but the ice at the terminus had melted down five feet. At a point 200 feet above the terminus the ice had melted down eight feet.

Disappearance of a shallow pond that lay immediately in front of the terminus in 1935 revealed the existence of a mass of stagnant débris-covered ice that either forms part of the present glacier or is left over from a time when the glacier extended farther down the mountain. In addition, residual masses of old laminated glacier-ice were found exposed in a stream-worn gully for a distance of one and one-half miles below the glacier. Similar buried masses of old glacier-ice had been observed in 1935 in gullies as far as one and one-half miles below the Wintun and Mud Creek glaciers, on the east and southeast flanks of the Peak. It is believed that these buried ice-masses date back to 1898, when the glaciers were observed to attain these lower reaches.

Lateral moraines containing considerable residual ice extend about one mile beyond the terminus of the *Hotlum Glacier*. These very probably date back to 1920, when, to judge from photographs taken in that year, the glacier filled the entire space between the moraines.

Bolum Glacier, situated on the north side of the Peak, was studied for the first time in 1936, and a base-line for future reference was laid down at its front. Below this line were found evidences of recession on a large scale similar to those existing below the *Hotlum Glacier*. Ice-impregnated lateral moraines extend for a distance of about one mile beyond its terminus, and old laminated ice is exposed in stream-cut gullies for a distance of one and one-half miles.

Whitney Glacier, situated on the northwest side of the Peak, also was studied for the first time in 1936. It has shrunken to a narrow ice-tongue flanked on both sides by high, broken masses of débris-covered ice. Lateral moraines containing residual ice extend for a distance of nearly a mile beyond the present terminus of clear ice. An ice-bridge 20 feet high stands at the place where the terminal moraine crosses the gulch below the glacier.

Glaciers of central Sierra Nevada

The following data are taken from the elaborate and beautifully illustrated report of C. A. Harwell, Park Naturalist of Yosemite National Park:

East Lyell Glacier had receded only 4.5 feet from the farthest point which it reached in 1935, but its surface had been lowered considerably by melting with respect to the frontal moraine.

West Lyell Glacier showed no appreciable change in length. Surface-water had exposed considerable ice in front of what heretofore appeared to be the terminus, and it is now considered probable that the frontal moraine rests largely or even wholly on old ice. Similar conditions occur at the fronts of all the glaciers in Yosemite National Park and render measurement of their variations in length uncertain.

Maclure Glacier, it is now evident from a cave-in at its apparent terminus, is fronted not by moraines properly speaking but by old masses of stagnant ice heavily mantled by morainic material. These débris-covered ice-masses extend more than 300 feet out beyond the apparent terminus composed of clear ice.

Dana Glacier, on September 29, 1936, had receded a maximum of 22 feet since 1935. This recession was measured at Station 3, near the middle of its broad front. At Station 2 the loss was 17 feet and at Station 5 was only four feet.

Conness Glacier, on September 29, 1936, showed a recession of nine feet at the front of its east lobe. The surface of the glacier continues to melt down rapidly.

Glaciers of southern Sierra Nevada

Oliver Kehrlein, Chairman of the Committee on Glacier Studies of the Sierra Club, contributes the following notes:

North Palisade Glacier, the southernmost of the larger glaciers of the Sierra Nevada, according to observations and photographs taken in 1936 by Mr. Cronemiller and forwarded by Regional Forester S. B. Shaw, showed no appreciable recession but continued lowering of its surface by ablation.

A special effort was made by Mr. Kehrlein during the summer of 1936 to obtain photographs of the glacierets in the Kern River and the Mount Whitney District. These glacierets, which are the southernmost ice-bodies in the Sierra Nevada, are slowly wasting away and are likely to become extinct in the near future if the present trend of climatic conditions continues unchanged. Photographs were taken of the following: (1) Glacieret in cirque north of Table Mountain, on Great Western Divide, west of Kern River Basin; (2) glacieret in cirque north of Milestone Mesa, also on Great Western Divide; (3) glacieret at base of east cliff of Mount Whitney; and (4) glacieret in cirque north of Mount McAdie and south of Whitney Pass.

Glaciers of Glacier National Park

The following data are taken from the report of Park Naturalist George C. Ruhle:

Blackfoot Glacier, which formerly was a continuous ice-mass mantling the northern slopes of Mount Blackfoot and Mount Jackson, and connected with the Pumpelly and Harrison glaciers, on the southerly slopes (as is shown on the topographic map made by the United States Geological Survey in 1900-02), is now divided into several separate ice-bodies. Of these the one lying between Mount Blackfoot and Mount Jackson, and designated Siksikaikwan Glacier, offers a particularly clean-cut front favorable for recession-studies and is measured annually. The record of its oscillations is as follows:

Year	Oscillations of ice-front in feet
1932-1933	+ 64
1933-1934	- 10
1934-1935	+ 8
1935-1936	-104

The terminus now is 42 feet back of the position in 1932.

Sperry Glacier, on September 18, 1936, had receded 97 feet from its position in 1935.

Grinnell Glacier, in contrast to Siksikaikwan Glacier, has been in constant recession since 1932. Its recession-record is as follows:

Year	Recession in feet	
1932-1933	0	
1933-1934	54	
1934-1935	43	
1935-1936	64	
Total and mean	161	40

Agassiz Glacier, today probably the largest single glacier in the Rocky Mountains of the United States, and situated but a few miles south of the Canadian Boundary, on September 3, 1936, was found to have receded not less than 465 feet from its position in 1935. During the three preceding years, however, it had receded a total of only 154 feet; hence, there is reason to believe that a special condition existed in 1936 that hastened the recession of the terminus. That special condition probably was the previous reduction of the ice-tongue by ablation to a thin ice-sheet.

Glaciers of Glacier Bay, Alaska

R. H. Sargent, Topographic Engineer of the Alaskan Branch of the United States Geological Survey, reports the following changes in the extent of the glaciers of Glacier Bay, as determined by a comparison of the plane-table map made in August, 1936, with aerial photographs taken in 1929 by the Aerial Survey Expedition of the United States Navy.

Reid Glacier had receded about 3700 feet since 1929 and had suffered considerable reduction in thickness. The glacier was actively discharging icebergs from its front at the time of the survey.

Lamplugh Glacier had advanced 500 feet at its western margin, but otherwise showed no material change since 1929.

Johns Hopkins Glacier appeared essentially unchanged in length, in spite of the discharge of numerous icebergs from its front. Reid Inlet, below the glacier, was covered with floating icebergs for a distance of more than two miles.

All of the non-tidal glaciers on the sides of Reid Inlet had receded slightly and had been reduced considerably in thickness since 1929.

Margerie Glacier was holding its own, in spite of the frequent discharge of icebergs. As was reported by Wm. Osgood Field, Jr., and Wm. S. Cooper, in 1936 (Trans. Amer. Geophys. Union, 17th Annual Meeting, 1936, p. 290), this glacier has remained essentially unchanged in length since 1926.

Grand Pacific Glacier, whose front is oscillating back and forth across the International Boundary, in 1936 was still entirely within Canadian territory, though close to the Line. Its front had advanced, in the aggregate, about 1000 feet since 1929.

Rendu Glacier also had advanced about 1000 feet since 1929, but was still non-tidal, its front resting on a mud-flat.

Carroll Glacier, at the head of Queen Inlet, since 1929 had receded two miles at its eastern margin and about half a mile at its western margin. It also had suffered a marked reduction in thickness.

Muir Glacier was the only one of the glaciers in Muir Inlet to be mapped. Its front had receded about one mile since 1929. As in previous years the Muir Glacier was very active, discharging immense quantities of ice from its front, and filling the inlet with bergs for a distance of several miles. Many of the bergs observed were more than 200 feet long and floated with about 40 feet of ice above the water. A number of bergs drifted down as far as Icy Strait.

Black Rapids Glacier

Black Rapids Glacier, according to brief preliminary advices received from Dr. J. H. Hance, Dean of the University of Alaska, has been actively advancing since the early fall of 1936. From press-dispatches it would appear that the advance is an extraordinarily swift one and that, if it continues, the glacier may threaten the highway to Fairbanks in the near future. More precise information regarding the actual extent of the advance, the rate of movement, and the probable nature of the cause, has, however, not yet reached the Committee on Glaciers.

U. S. Geological Survey,
Washington, D. C.

REPORT OF THE COMMITTEE ON EVAPORATION, 1936-37

S. T. Harding, Chairman

The membership of the Committee for this year is as follows:

Harry F. Blaney, 600 Federal Building, Los Angeles, California
N. W. Cummings, San Bernardino Valley Junior College, San Bernardino, California
Robert Follansbee, 403 New Post Office, Denver, Colorado
J. A. Folse, Museum of Science and Industry, 56th Street and Lake Michigan, Chicago, Illinois
Robert E. Horton, Voorheesville, New York
Ivan E. Houk, 1024 U.S. National Bank Building, Denver, Colorado
R. E. Kennedy, 1577 Jasmine Street, Denver, Colorado
G. F. McEwen, Scripps Institution of Oceanography, La Jolla, California
Carl Rohwer, Colorado State College, Fort Collins, Colorado
C. M. Saville, 53 North Beacon Street, Hartford, Connecticut
Thorndike Saville, New York University, University Heights, New York
S. T. Harding, 12 Engineering Building, Berkeley, California, Chairman

Messrs. Follansbee, Folse, Horton, and Houk are new members who accepted appointment on the Committee in 1936.

The Committee has been working on the chapter on Evaporation from Free-Water Surfaces for the proposed Bulletin on Hydrology in the Physics-of-the-Earth Series of the National Research

Council. The Chairman of the Committee had been asked to prepare such a chapter and has sought the assistance of the members of the Committee in its preparation. A first draft was sent to the members of the Committee in December, 1936, with a request for criticism. Several carefully prepared and helpful reviews of this draft as well as discussion of the subject of evaporation were received from members of the Committee. A second draft, condensed to the length allotted in the Bulletin for this chapter, is nearly completed. If time permits, it will also be sent to the Committee members for further comment. This work has been the only direct activity of the Committee during the year.

The discussion within the Committee of the items that should be included in such a treatment of evaporation and the extent of the discussion of different methods of determining the amount of evaporation that is needed has served to emphasize the comments made in the report of the Committee for 1935-36 regarding the different points of view in this field. Such discussion has also emphasized the lack of adequate observational data to settle such differences in opinion. In the absence of such observational data, such differences will continue to be differences in opinion without much progress toward their settlement.

As a result of its work in preparing this chapter on evaporation, including the general principles involved and the present status of knowledge, the Committee should now be in a position to plan an adequate investigational program to meet many of the present deficiencies in information in this field. If an agency having the interest in the subject and funds for the conduct of such work could be found, the Committee should be able to be of assistance in planning such work. Several past investigations have been carefully conducted but none has been sufficiently comprehensive to meet all of the questions raised regarding their results.

For the coming year, it is planned to complete the chapter previously mentioned. Definite plans for further activity have not, as yet, been made. An attempt could well be made to work out a specific program for a general study of evaporation from water-surfaces that would meet present needs in the hope that some agency could then be found which might undertake such work.

12 Engineering Building,
Berkeley, California

REPORT OF THE COMMITTEE ON ABSORPTION AND TRANSPIRATION, 1936-37

Charles H. Lee, Chairman

The current year has been one of great activity in the field of hydrology. This is true not alone of experimental work, but to an even greater extent in the practical application of known facts and principles. Demand for the latter has arisen throughout the United States in the numerous public and semi-public projects which have been initiated in recent years. Many of these projects involve the conservation and use of water, the protection and prevention from floods, and the disturbing effects which large improvements often have upon the natural hydrologic balances. As a practical result of this activity, little time has been available for writing of papers and work of the Committee.

With this general statement as a prelude, let the fact be known that this Committee, after several years of uncertainty as to whether its annual reports could be published in full, is this year furnishing the editorial staff with a pleasant surprise by submitting a short report. This does not mean that a precedent is being set for the future, however, for with all the current activity new material is being accumulated which may burst forth at future meetings as a veritable flood.

The original membership of this Committee expired at the end of last year; the Chairman was reappointed for a new term and several of the old members have continued to serve. The full membership has not yet been selected, however, and its announcement will be deferred until next year's report.

The Committee's review of current work and of reports is very incomplete. Among those which have come to attention is the study being made by the United States Geological Survey of rainfall and runoff during the floods of March, 1936, in northeastern United States. One objective of this study is to determine the residual between the total amount of water available for runoff and the total surface-runoff. The residual was taken as reflecting the amount of water left in the basin as surface-storage and infiltration and the evaporation. Precipitation at 1500 stations and snow-depth and water-content at several hundred locations were analyzed. These points lay within 500 drainage-basins in which flood-discharge was measured at gaging-stations. The results will be published as chapters in Water Supply Papers Nos. 798, 799, and 800.

The current experimental work of various governmental agencies described in previous reports of the Committee is continuing and will be reported upon in next year's report, together with newly initiated research work.

Among recent papers, attention is drawn to that entitled "Direct accretions to ground-water from rainfall" by S. T. Harding, a member of this Committee. This excellent paper is being presented at the symposium on infiltration and losses at the present meeting of the Section of Hydrology. It includes a bibliography.

58 Sutter Street,
San Francisco, California

REPORT OF THE COMMITTEE ON RUNOFF, 1936-37

W. G. Hoyt, Chairman

Since the last meeting of the Section of Hydrology there has been a change in the organization and membership of some of the research-committees, one relating to rainfall, of which Merrill Bernard is Chairman, and one relating to runoff, were created to replace the one committee which had functioned heretofore on both rainfall and runoff. This action by the officers provides for greater participation of the members of the Section in committees, and is a step well worth while. The personnel of the Committee as of May 1, 1937, is as follows:

H. K. Barrows
M. M. Bernard
E. S. Cullings
R. W. Davenport
R. S. Goodridge
R. E. Horton
I. E. Houk
W. G. Hoyt
Joseph Jacobs
F. T. Mavis
A. F. Meyer
C. R. Pettis
F. F. Snyder
H. C. Troxell
C. O. Wisler

I consider it an honor to act as Chairman of the Committee on Runoff but regret, however, that I have been unable as yet to coordinate thoroughly the work of the Committee or to inform myself adequately on many runoff-experiments and research-problems. Consequently, my report will be very brief and informal.

During the past year the Section of Hydrology has lost two men who were vitally interested and have contributed greatly in problems relating to meteorology and runoff. I refer to the untimely passing of M. W. Hayes of the United States Weather Bureau and D. L. Yarnell of the United States Bureau of Agricultural Engineering. The work of these men will live after them.

The Section should be proud of the fact that one of its members, Mr. Bernard, has been appointed Chief of the River and Flood Division of the United States Weather Bureau, a position formerly occupied by Mr. Hayes.

As to the recent past and the future, the outstanding floods of March, 1936, and the Ohio and Mississippi River floods of January, 1937, have come and gone. Students of meteorology have assured us that in all probability the downward trend in precipitation will soon be reversed, and if this is so the devastating drought-experiences of the 30's will be things of the past. The recurring droughts and devastating floods have, however, been responsible for greatly increasing activities in hydrology along many fronts. One phase of these activities relates to the steps being taken to make the nation water-conscious, of which the Upstream Engineering Congress held last September was probably the most outstanding. It is encouraging to report that Messrs. Horton, Lowdermilk, Saville, Sherman, and White, and other members of the Section of Hydrology took active part in these proceedings and made valuable, sound, and scientific contributions.

Another measure of progress is shown by the increased activities in experimental research relating to the control of surface-runoff and the conservation of water supplies. These activities cover areas in almost every State by many different organizations. In view of the fact that in Appendix B of the Report of the Committee on Runoff for 1934-35 (pp. 411-416, 16th Annual Meeting, part 2) there are listed the organizations engaged on the research-work mentioned, together with locations; the details are not included in this report. These activities embrace the extensive work being done by the following: The United States Soil Conservation Service at their large experimental areas in Ohio, Texas, and Colorado, and at demonstration-areas in many States; the extensive runoff-experiments of the United States Forest Service at the San Dimas

Area in Sout.. . California, at the Coweeta Area in North Carolina, besides additional plot-work at all of their experimental stations; the work of the United States Bureau of Agricultural Engineering, the United States Geological Survey, the Tennessee Valley Authority, the National Bureau of Standards, the University of Illinois, the University of Iowa, the Los Angeles Flood-Control District, and many other agencies and individuals.

A third important measure of the increased public interest in hydrologic matters is evidenced by the work of the United States Geological Survey in studies and presentation of basic meteorological and hydrologic data relating to the droughts of 1936, the major floods of 1935 and 1936 in Texas, and the floods of March 1936 in Northeastern United States. Of very notable importance is the report of the President's Drought Committee on the future of the Great Plains. Much of the data contained in their report was compiled by members of the Section of Hydrology.

Of more than passing interest to the members of the Section of Hydrology are the studies being made by the Water Resources Committee of the National Resources Committee with respect to deficiencies in hydrologic data and recommendations being made to overcome such deficiencies.

In connection with all of these activities, as I see it, there rests on the Section of Hydrology, both individually and collectively, a distinct obligation to assist these studies in every possible way, to recommend sound engineering and hydrologic practices, and to promote factual knowledge regarding runoff in all its phases.

U. S. Geological Survey,
Washington, D. C.

REPORT OF THE COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1936-37

(Interpretation of soil-moisture problems by means of energy-changes)

F. J. Veihmeyer, Chairman

The annual report of the Committee is intended to be a symposium on the subject of soil-moisture. The nucleus of the report is a paper prepared by the Chairman and N. E. Edlefsen of the Committee. The paper was written for the purpose of broadly reviewing the field and to stimulate discussion. It was sent to the members of the Committee and to a selected list of investigators who have shown interest in the subject with a request for comments, opinions, or criticisms. The replies follow the paper and are published verbatim.

INTERPRETATION OF SOIL-MOISTURE PROBLEMS BY MEANS OF ENERGY-CHANGES

F. J. Veihmeyer and N. E. Edlefsen

Terms used in connection with soil and water are helpful in conveying some impression in a concise way of the moisture-condition of the soil under discussion. These terms, however, in many cases are merely qualitative and do not precisely define the condition. The terms in some cases suggest sharp distinctions in the manner in which the water is held in the soil which do not seem to exist.

In soil-science as in other branches of science there is a tendency to build up a picture of the condition under consideration even though it is known that the details which make up the picture are incorrect. For instance, the elementary picture presented for the structure of an atom, in which the nucleus was described as the massive material at the center and the electrons as much lighter particles revolving around it, was probably not entirely correct. The picture, nevertheless, did serve a useful purpose. Energy-changes, however, are the essential phenomena observed. The hypothetical picture of the atom was merely one that seemed to account for the phenomena.

The usual classification of soil-moisture into gravitational or free, capillary, and hygroscopic water is perhaps helpful from some standpoints, but leads to confusion because water, which by definition is capillary, may become gravitational water and may be made to drain away from the soil under certain conditions. Soil may absorb large quantities of water from the air and from the viewpoint that this absorbed moisture is condensed on the soil-particles, or on the water-surfaces in the soil, it is hygroscopic water. Yet plants can use some of this so-called hygroscopic water; and if the soil is left in contact for long periods with air containing sufficiently large quantities of water-vapor, the soil may absorb so much moisture that some of it will drain away and become free or gravitational [see 16 of references at end of paper]. There

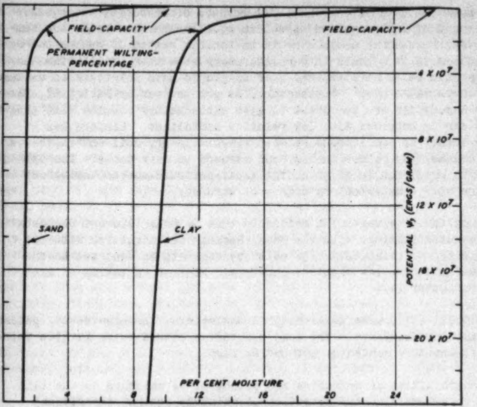

FIG. 1—POTENTIAL AND SOIL-MOISTURE
(POTENTIAL CALCULATED FROM VAPOR-PRESSURE MEASUREMENTS)

is no sharp distinction between free, capillary, and hygroscopic water. The same criticism might be applied to other arbitrary classifications.

In a study of soil-moisture, just as in that of atomic structure, our picture of the mechanism might be faulty. It is convenient, therefore, to rely upon such measurements as energy-changes. The most helpful conception of soil-moisture phenomena, whether from the viewpoint of its use by plants, the way it is held in the soil, or its movement is, we believe, gained by consideration of energy-relations. The energy necessary to remove the water from soil can be measured. The results of such measurements show that the energy is a continuous function of soil-moisture. There appear to be no discontinuities in the curve representing the relation between soil-moisture content and the energy required per unit-mass to remove water from the soil to some place of reference. This relation is shown in a general way in Figure 1. The accuracy of the measurements now available justifies the assumption of a linear relation for the major parts of the curves. It would seem, therefore, that except in degree there are no particular moisture-contents at which the water in the soil can be defined as being in a different state than at others.

The application of the principles of mechanics to the study of soil-moisture has led to a better understanding of soil-moisture conditions and of the forces acting on soil-moisture. It has been found desirable to introduce a mathematical function, called a potential function [6, 9], which is merely a matter of convenience for analysis just as moment of inertia, radius of gyration, gravitational potential, and electrical potential are used in certain types of analyses.

The potential may be given the symbol ψ and is defined [3, 9, 10] by the equation

$$\psi = -\int_A^B f \cos \theta \, ds$$

in which f represents the field-force acting per unit-mass of moisture, ds is an element of distance along the path, A is a reference-point usually taken as a free-water surface, B is the point in question, while θ is the angle between f and ds. This may be stated in words as the work per unit-mass done against the field-forces in moving water from the reference-point to the point in question. There is strong evidence that the potential is a single-valued function of the moisture-content although some investigators question this. It is believed that the lack of equilibrium has been the cause of some questions. The answer will require further study. This function, as defined above, has been called capillary potential and pressure-potential. We prefer in this paper to speak of it simply as potential or moisture-potential since it is clear that it refers to soil-moisture. The words capillary or pressure infer a mechanism which might be incorrect. Figure 1 shows idealized potential moisture-content curves for a clay and sand covering the range of soil-moisture between limits usually found in the field. The potential was calculated from vapor-pressure measurements.

The potential is rationally related to other properties of soil-moisture. A measurement of any of these properties, therefore, is sufficient to calculate the potential. The methods which seem to have possibilities for measuring the potential of water in soil are: Vapor-pressure; freezing-point; dilatometer; seed-absorption; centrifuge; porous-clay apparatus; osmotic membranes, dielectric; and rate of drying. A brief discussion of the present status and limitations of these methods is pertinent at this point.

A number of investigators have discussed [7, 17, 23, 31] methods of measuring the aqueous vapor-pressure of soils. The length of time required to obtain equilibrium when soils are suspended over solutions of known vapor-pressure, as is done in the static method of making the determinations, is a serious objection to it. Tests in our laboratory show that equilibrium was not reached in more than 30 days when soils were exposed over sulphuric-acid solutions in vacuum desiccators held in a constant-temperature room. Furthermore, as pointed out by Puri [16], the difficulties with high relative humidities are too great to give satisfactory results with present technique, but fair results can be obtained with low relative humidities. Linford has further demonstrated that there cannot be equilibrium between relatively dry soil and vapor over the free surface of water at the same temperature as has been assumed in many cases. The method proposed by one of us [7] seems to hold promise of obtaining vapor-pressure curves throughout the entire range of soil-moisture with a satisfactory degree of accuracy.

The most recent discussion of the freezing-point method is that by Schofield and Da Costa [19]. We find that the freezing-point readings with the usual Beckman technique is, with the majority of the soils tested, limited to relatively high moisture-contents in contrast to the vapor-pressure method which is suitable for low moisture-contents. Another variation of the freezing-point is by using a dilatometer [4].

Another method, devised by Shull [21], uses small natural osmometers, Xanthium seeds, placed in contact with soils at known moisture-contents. The seed-absorption method seems to give fairly consistent results at low soil-moisture contents, but not at high.

Another method which has possibilities of measuring the potential of moisture in the soil at various moisture-contents is by determining the retention of moisture against centrifugal forces of known magnitudes [5]. The only wide use of the centrifugal method is at one force, that of 1000 times gravity. The moisture retained in a small pat of soil prepared and centrifuged in a specified manner at 1000 times gravity is called the "moisture-equivalent." The results of the procedure give remarkably concordant results [27]. The moisture-equivalent has, therefore, become a widely used so-called soil-moisture constant to measure the relative water-holding capacity of soils even though it is the result purely of an arbitrary procedure [25, 27]. The fact that the moisture-equivalent is about equal to the "field-capacity," mentioned later, of fine-textured soils increases its usefulness [28].

It follows from theoretical consideration and has been demonstrated experimentally that at equilibrium the sample being centrifuged decreases in moisture-content from the periphery toward the axis. This means that the gradient of the potential is equal and opposite to the force tending to throw water out of the soil. It seems, therefore, that if the potential at the boundary-conditions were known, the method would be a means of measuring the potential as a function of moisture-content.

The potential can be calculated from measurements of the "suction" on water which soils at known moisture-contents can produce. The usual procedure is to spread a layer of soil over the surface of a porous-clay cup which contains water under known pressure. When the moisture in the soil is in equilibrium with the water in the cup, the potential of the water in the soil is equal to the potential of the water inside the cup.

The porous clay-cup method which is so intimately associated in many cases with the concept of a potential, but which really is only one of the several methods which can be used to measure it, also has its limitations. "Suctions" with such a system ordinarily cannot exceed a pressure-equivalent to one atmosphere, or about 1000 cm of water. In fact, only "suctions" of much less than this have been maintained with the equipment now available.

Potentials of less than that equivalent to a pressure of one atmosphere cover a very small part of the range of soil-moisture within which plants can readily obtain a supply of water [7]. For instance, in a Yolo silt loam a "suction" equivalent to 756 cm of water was obtained with a Livingston "auto irrigator" [15] when the moisture-content of the soil was at about 13 per cent on a dry-weight basis. The "field-capacity" [28] of this soil, that is, the moisture-content the soil will have after the excess moisture following irrigation or rain has drained away and after the downward movement of moisture has materially decreased, which usually takes place within two or three days after the application, is 15.9 per cent. Yet plants can extract water readily from this soil until the moisture-content is reduced to about 8.8 per cent. This moisture-content is the "permanent wilting-percentage" of the soil, a term used to mean that moisture-content at which plants wilt and do not revive when placed in a moist chamber until water is added to the soil [12, 26]. It is the moisture-content below which plants cannot readily obtain water. Because of the difficulties in obtaining precise results in soil-sampling and in determining exactly when a plant is wilted, the permanent wilting-percentage as used by us represents a narrow range of soil-moisture within which wilting takes place. This can usually be measured to within one per cent of soil-moisture. We believe that the permanent wilting-percentage is the important soil-moisture condition for the interpretation of plant and soil-water relations, since it limits the normal activities of the plants. It is characteristic of the soil. In other words, it is independent of the kind of plant or variation of climatic conditions likely to be met with in the field [29].

Experiments with fruit trees and other plants [2, 12, 13, 20, 24, 30] show that soil-moisture is extracted from the soil at a uniform rate for all moisture-contents above the permanent wilting-percentage. The rate seems only to depend on the climatic conditions and on the age, density, and type of crop grown. Neither the growth of the plant nor the growth of the fruit seems to be altered by varying the moisture-content from about the permanent wilting-percentage to the field-capacity. A marked effect on the plants is seen only when the rate of use of water shows a decided decrease which occurs when the permanent wilting-percentage has been reached. After the permanent wilting-percentage of the soil in contact with the absorbing roots is reached, the rate of extraction of water is materially reduced, the plant usually begins to shed its leaves, and soon transpiration is reduced to a very low amount. For practical purposes, therefore, the permanent wilting-percentage may be regarded as the minimum moisture-content a soil in the field, except in a thin layer at the surface, can reach. The surface-layer, of course, loses a portion of its water by direct evaporation and it might reach a moisture-content much lower than the permanent wilting-percentage. It has been shown [1, 24], however, that the depth of soil affected in this way is rarely more than eight inches.

The other methods mentioned above for measuring the potential of water in soils, that is, osmotic membranes, heat of wetting, dielectric, and rate of drying, have not been used so successfully as those discussed above, but it is believed that they might be if properly developed. As has been pointed out [7], the variation in potential is comparatively slight between the field-capacity and the permanent wilting-percentage as compared with variation in potential below this moisture-content. For instance, to evaporate or to transpire one gram of water from saturated soil requires only about one per cent less energy than when the moisture-content is at the permanent wilting-percentage.

The fact, mentioned before, that the potential is a continuous function of the soil-moisture content and that there are no sharp breaks in the curve, suggests that to arbitrarily select a point on the curve and to find that it has greater significance either biologically or physically than other points in its vicinity is fortuitous. As pointed out before, the wilting process is not sufficiently abrupt to define a definite point on the curve.

The fact, mentioned earlier, that soils do not dry out much below the permanent wilting-percentage except in a shallow layer which is affected by direct evaporation, and that the permanent wilting-percentage is the moisture-content at which growth of plants is retarded, suggests its use as a soil-moisture constant. The field-capacity represents the approximate upper limit of moisture-content which can be stored in a soil for use by plants under field-conditions. An approximately correct statement is that the difference between the amount of water required to saturate the soil and the field-capacity is that which will drain away and contribute to the underground reservoir. Present information seems to indicate that the potential of soil-moisture is about the same for all soils when they are at their permanent wilting-percentage. This seems likewise to be the case at field-capacity. Further evidence must, however, be had before this conclusion can be unqualifiedly drawn.

The potential function is also an aid in the interpretation of soil-moisture dynamics, especially in unsaturated soils [8, 11, 14, 18, 9]. There are, of course, other means of analyzing dynamic problems of soil-moisture but the concept of the potential of the water in soils has been found to be very convenient, not only from the viewpoint of use of water by plants but also from that of soil-moisture movement. The rate of change of this function with distance in any direction is a force tending to move moisture in that direction. For example, when water is placed on the surface of a large area of comparatively dry soil there are two forces tending to pull it downward. The gradient of the gravitational potential is a force acting downward on every particle of water and, in addition, there is a gradient of the moisture-potential in the region of the water-front also acting downward (the dry soil below pulls on water in the moist soil above). The latter force acting on the mass of water in the soil is constant with time during the wetting process, whereas the total gravitational force acting on the mass of water in the soil is directly proportional to the mass of water in the soil and does, therefore, increase with time. The force existing due to the gradient of the moisture-potential plays an important role in the distribution of water in a soil in the early stages of wetting. As the water-front moves down, however, this force becomes of less importance. This combination of forces causes a comparatively rapid downward movement of the water-front at first but gradually decreases with time until a constant rate is reached. With some soils this constant rate is reached quickly.

If the supply of free water to the surface is stopped, a gradient of the moisture-potential is developed at the surface as water is drawn out of the surface-layers. This gradient produces a vertical force, but here it is in opposition to gravity. If the soil has only been supplied with enough water to wet down three or four feet, the gradient of the potential at the top and bottom represents a large portion of the total force acting and produces a rapid distribution of water in the soil-mass. Under these conditions a state of very slow motion and nearly uniform moisture-content is reached in two to three days after irrigation. The flow of moisture under a given driving force decreases with moisture-density. The moisture-content found under such conditions is what we have called "field-capacity." It should, however, be recognized that this is not an equilibrium condition but merely a condition of slow motion as compared with the rate at which water is pulled out of the soil by plants. The moisture-content will change only slightly in periods much longer than those usually lapsing between applications oi water [24].

Since the motion of water at moisture-contents lower than field-capacity is so slow, it would seem that the rate of movement to the surface and hence the rate of evaporation-loss would be small. This fact has been demonstrated by many experiments and leads to the conclusion that under practical field-conditions one cannot appreciably lessen by cultivation the amount of water evaporated from the soil. It has been shown [24] that under arid and semiarid conditions the losses that occur from soils are chiefly due to plant-transpiration.

The fact that the motion of soil-moisture is so slow has a practical bearing on the use of soil-moisture by plants. Soil-moisture does not move fast enough through appreciable distances to supply the needs of growing plants [24]. In other words, rate of movement of soil-moisture is relatively slight as compared with the rate of growth of roots.

When water has been allowed to saturate a soil to a water-table 30 or 40 feet below the surface and then is shut off, gravity is the predominating force acting on the soil-moisture, although there is a gradient of the moisture-potential developed in the soil-mass near the surface in opposite direction to gravity. The total force tending to drain the soil is less in this case than when there is a gradient of the moisture-potential at the lower water-front. The motion is, therefore, very slow. Since there is a great deal of water in the soil, as much as 105 days or more [3] may be required before the upper six feet of soil is drained to field-capacity, a process requiring only three or four days when only the top three or four feet are wet.

This slow downward motion over long periods of time, when large areas of soil are wet to considerable depth, furnishes a much larger contribution to the underground water-table than is sometimes thought. Thus water-spreading in arid regions may add appreciable quantities of water to the underground basin long after the spreading occurred.

The rate of intake of water at the surface is limited by the rate at which water can move through the soil. Any studies of infiltration, therefore, must take into account these forces as well as other factors if generalizations of wide applicability are to be drawn. For example, considerable variation in the depth of water on the surface of porous materials will only slightly affect the rate of infiltration; while texture, structure, and other conditions included under the term macrostructure have decided influence on the rate. In some cases clays have higher rates of infiltration than do sands [22]. In any case, however, an integration of all of the forces acting on the mass of water must be considered if a clear understanding of the problem is to be attained.

Summary

The physical properties of soil-moisture which influence such measurements as vapor-pressure, osmotic pressure, freezing-point, etc., can be expressed as changes in energy. The introduction of a potential function is convenient for analysis of problems involving changes of energy.

The curves showing the relation between the potential and soil-moisture are smooth curves indicating that the potential is a continuous function of the moisture-content. In other words, these curves illustrate the degree with which water is bound by the soil as the moisture-content varies. It is, therefore, questionable whether it is justifiable to arbitrarily select a moisture-content and say that below this the water is bound and to infer that it is not bound

above this content. Likewise, it would be questionable to arbitrarily select a point on the curve and to say that above this point water is available to plants and not below. But many tests with different soils and plants show that the availability of water to plants is affected only when the moisture in the soil in contact with roots is reduced to a rather definite moisture-content, the permanent wilting-percentage, defined herein as a narrow range of moisture within which wilting takes place. The permanent wilting-percentage falls in the region of greatest curvature of the potential-moisture content curve as we have drawn it, which lends support to its selection as an important soil-moisture content.

Although arbitrary measurements and classification of soil-moisture are useful in some cases, it is more rational to study this subject from the standpoint of energy-relations. The introduction of a potential function is helpful in this study not only from the standpoint of the use of soil-moisture by plants but perhaps more so from the standpoint of infiltration and movement of moisture in the soil. An attempt has been made herein to review some of the pertinent implications of this mode of attack.

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DISCUSSION

W. W. ALDRICH AND R. A. WORK, United States Department of Agriculture, Bureau of Plant Industry, and Bureau of Agricultural Engineering, respectively--Although fruit trees have not generally shown any marked growth-differences with variations in soil-moisture [see references 3, 4, 5, 6, 8, 9, 10 at end of remarks] between field-capacity and permanent wilting-percentage, an apparent exception has been observed in the case of Anjou pear in Meyer clay adobe-soil near Medford, Oregon. It has been shown by yield [7], by rate of fruit-growth and by stomatal opening [1, 2], and by tree-wilting [11] that water-deficits in the tree occurred while the average soil-moisture (as measured by standard methods, using soil-cores one foot in length obtained by the improved soil-tube) was definitely well above the permanent wilting-percentage. Furthermore, the rate of soil-moisture decrease in this clay adobe-soil has frequently been found to slow down before the permanent wilting-percentage was reached [7]. Since in this soil there are small volumes of soil without roots, it may be that, when the above tree responses were observed, the moisture in the soil in immediate contact with the roots had reached the permanent wilting-percentage while the moisture in the soil only a centimeter or so from the roots was much higher but was moving to the roots too slowly to prevent water-deficits in the tree.

It is not known to what extent the soil-type is responsible, since it has not been possible to extend these studies of Anjou pear to lighter soils. In a heavy clay-soil both the evaporating power of the air and the ratio of leaf-area to root-area seemed to affect the sensitivity of Anjou pear [2] to water-deficits even when the average soil-moisture was well above the permanent wilting-percentage. Anjou has also shown this inverse relation between rate of fruit-growth and evaporating power of the air in lighter soils. It therefore seems characteristic of the Anjou pear that the water-supply to the leaves during periods of high evaporating power of the air may be limited by the amount of root-area. To what extent this may be true of other pear varieties or of other fruit-tree species is not clear.

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G. B. BODMAN, University of California--The points of view with respect to soil-moisture as expressed in the article are very largely in accord with my own. Comments are given below concerning certain of the statements which it contains.

Continuity of moisture content-energy relations: It is evident that the article is referring primarily to the water which can be removed by heating to 105°-110° C, which includes the greater amount of the soil-moisture and much more than the range affected by wetness-fluctuations in the field. This is the agriculturally important part. However, the water-content referred to the ordinary oven-dry basis depends upon a purely arbitrary selection of the base for calculation. If zero-wetness is taken to be that water-content at which further heating produces no further loss in water, or in other words if the entire range of water-content is considered, the relationships are somewhat altered. If this point of view is adopted, then before complete desiccation is obtained, a certain discontinuity appears in the curve representing the relation between soil-moisture content and the energy required to remove unit-mass of water from the soil to a given reference-point. This may be illustrated by consideration of unpublished results obtained by Bodman and Hoseh [see 1 of references at end of remarks]. It was found that hydrogen-peroxidized clays, having a settling velocity at 20° C of less than 3.47×10^{-4} cm/sec, which had been extracted from a representative group of four Californian soils, were materially changed as to their heats of wetting-water content relations by such desiccations as resulted from heating to temperatures in excess of 350° to 400° C.

The heat of wetting may be traced in its relation to the water-content from high to low water-contents; if this is done, the heat of wetting is found to rise at first slowly, then more rapidly, until a maximum is reached at that moisture-content corresponding to a temperature of about 400° C. Such desiccations as are produced by heating to higher temperatures develop in the clays such a rearranged state that the heat of wetting curves then rapidly falls until moisture-contents corresponding to temperatures of over 500° C are reached. In this highly desiccated condition, the heats of wetting were found to be very low (about 5 cal/gm). Beyond these temperatures the experiments did not go. It is our opinion that crystal-lattice water was being removed at temperatures between 350° and 450° C.

When considering the energy-water content relations it is rational to consider the entire range, in which case an actual discontinuity does appear to exist, as evidenced by the sharp maximum referred to above, somewhere near absolute desiccation. However, this is certainly far below the range of water-content having common practical importance.

Infiltration considerations: The article states that the gradient of the moisture-potential in the region of the water-front while water is penetrating comparatively dry soil may be regarded as constant with time during the wetting process. This may not be entirely true counting from the time when the water first begins to enter the soil. In the earliest stages of penetration there may be a region which is virtually water saturated from soil-surface to advancing water-front. Later on this is certainly not the case. Experiments reported by Bodman [2] are in close agreement with the remaining statements concerning the infiltration of water into soils and in addition it has been pointed out that the moisture-content of the soil is also an important factor affecting the rate of entry.

Nomenclature of function: There appears to be much in favor of using the term moisture-potential or simply potential. However, there is also some advantage in the use of the concept and term pressure-potential or capillary potential when first introducing the general idea of potential relations to the study of soil-physics.

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C. W. BOTKIN, New Mexico College of Agriculture--We studied some phases of the movement of moisture in alkaline soils a few years ago and found that the problem was complicated by a number of factors which were difficult to control. Our work in that connection is published in Station Bulletin No. 160 and in the Journal of Agricultural Engineering for September, 1927. From our observations the properties of the soil-colloids, both chemical and physical, determine the moisture-relations. Gravitational forces have little effect where the soil contains high percentages of colloids. In fact, in some instances, we found that the increased head of water decreased the rate of penetration into the dry soil. This was attributed to the compacting of the moistened colloidal material under the added pressure of the column of water.

W. GARDNER, Utah State Agricultural College--I have attempted at various times and in various ways to present some of the fundamentals of the dynamics of soil-moisture and have found it quite out of the question to dispense with this concept. I appreciate the significant fact that many research men in this field prefer to avoid extensive use of mathematical analysis. It is for this reason, I presume, that the language of dynamics has not become a part of the soil-physics vernacular. On the other hand, if I may be pardoned for venturing the suggestion, the naive tautological soil-physics literature of a day which we hope is past suggests, it seems to me, a fundamental weakness requiring modification, and I think the present discussion is a step in the right direction.

It has seemed to be necessary to make use of some such modifying adjective as "capillary" to distinguish the potential arising from tension or pressure in the fluid from that due to gravity. The curvature of the air-water interface in a capillary tube seems to be causally related to the tension in the water and it has seemed appropriate to characterize soil-moisture phenomena involving an air-water interface as capillary phenomena. At any rate they are frequently so characterized. I do not believe the adjective "moisture" would be suitable for indicating this distinction.

It seems to me it is worth while emphasizing the fact that the capillary-potential-soil-moisture curves of Figure 1 are characteristic of the soil. In a recent paper which is in process of publication, I undertook to suggest the possibility that the curve (or the parameters which determine it) would serve to identify the soil. If so, numerical values for a comparatively small number of such parameters would furnish a rational basis for soil-classification. It is possible, of course, that soils differing in certain physical characteristics might have the same curve. It is to be hoped, nevertheless, that studies in the laboratory of the various soil-types will include the determination of this characteristic curve.

G. A. GREATHOUSE, United States Department of Agriculture, Bureau of Plant Industry--The interpretation by the authors of the soil-moisture problem in terms of energy-changes enables us to express the soil-moisture on a more accurate basis. They state that the energy necessary to remove the water from soil can be measured and that the results of such measurements show that the energy is a continuous function of soil-moisture. The writer is more familiar with the application of physical methods to plant rather than to soil-water relations. However, the same fundamental and basic principles apply to both fields.

Similar results to those discussed in the paper have been found for plant-tissue [see 1 of references at end of remarks]. Earlier it had been commonly accepted that with biocolloidal systems there was a definite temperature (-18° to -20° C) at which all of the freezable water associated with the cell constituents would be frozen. The variable used on the plant-tissue was temperature, and as temperature changes so does vapor-pressure, which, in turn, is a measure of the activity of the water held by the plant-tissue or soil-complex. The results secured on plant-tissue indicate quite definitely that the water associated with the tissue cannot be thought of as consisting of a constant fraction of the total water when different forces (low temperature) were applied.

The activity of water may be taken as a measuring rod defining the physical status of the water present in a system. When the activity of water is varied it is an indication of a corresponding change in the free energy-content of that water. There are, in general, two ways by which the free energy-content of a solvent may be decreased, temperature remaining constant. The first is that which is characteristic of ideal dilute solutions in which the entire energy-change during dilution consists of a kinetic energy-exchange between the molecules of the added solvent and the molecules of the solvent already present in solution. The second way in which the free energy-content of the solvent may be decreased is that which is characteristic of concentrated solutions. It is important in this connection to recall that while the activity of the water in either of these two systems might be the same (and would be at equilibrium) the fate of the free energy lost by the water in coming to this activity is different for the dilute and concentrated solutions.

The soil or biological system does not absolutely follow either of these types of solutions; the dilute solutions of crystalloids tend toward ideal dilute solutions while the concentrated solution of some crystalloids and colloids tend toward exhibiting the properties of ideal concentrated solutions. Whether or not the system follows the ideal dilution or concentrated-solution laws can be determined only by a comparison of the total free energy-change in the water, ΔA, with the total energy lost from the system, ΔE, during the process of dilution. When $\Delta E = 0$, the laws of dilute solutions are being obeyed and there is none of the influence upon the activity of the water due to the gravitational forces between components of the system. If $\Delta A = \Delta E$, the entire change in the activity of the water is due to these forces.

Katz [2] has shown that colloids follow the laws of concentrated solutions. He has likewise shown that water associated with a colloid in amounts up to that required to show an activity of 0.20 to 0.40 on the water-content—water-activity curve for that colloid is bound to or associated with the colloid primarily in accordance with the laws of ideal concentrated solutions, but that the additional water needed to bring the activity to any higher value on the curve is bound to or associated with the colloid mostly in the manner which is characteristic of dilute solutions.

The writer has found that the amount of water associated with colloids (agar and fibrin) between activities 0 and 0.30 is less than that between activities of 0.3 to 1.0, also that the water associated with the colloid at activities 0 to 0.3 requires a greater force to remove it than that between 0.3 to 1.0 (unpublished). Thus the energy necessary to remove the water from a plant or soil-complex must vary with the moisture-content, composition, etc., and the energy-relations should be a continuous function of soil-moisture.

There are certain difficulties encountered in the measurement of the force with which water is held in biological and soil-systems, from activity-measurements alone. A knowledge of the water-activity—water-content curve for each component separately is necessary for such a calculation. Many of our biological or soil-systems cannot be readily and accurately analyzed into their components. What then is our next best procedure to arrive at the true value of the water held in these complexes? Newton and Gortner, and others have measured the deviation between two arbitrary points on the water-activity—water-content curve of the colloidal system, from those on the curve which is calculated for the system had it been following the laws of dilute solutions between these points. This procedure does not give true values for the quantity of water associated with the colloid at the activity of water at which the measurement was made. Neither does the use of this procedure imply that the value for the water associated with the colloid obtained would vary if the arbitrary points on the curve were changed.

Irrespective of how difficult it may be to arrive at the true value of water associated with biological and soil-systems, it is not difficult to test the methods so far devised for this determination to see whether or not they can be interpreted in terms of the theory just briefly outlined.

In complex systems as soil and plants it should be kept clearly in mind that it is equal distribution of forces, not equal distribution of water, which prevails in dynamic water-equilibrium.

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M. R. HUBERTY, University of California--The authors discuss the thermometric method of determining the freezing-point without reference to the dielectric method of measurement. While it is probably true that Alexander has not yet published his findings, the results he was obtaining last fall gave good promise. The authors doubtless had this in mind when they mentioned the dielectric method of measuring the potential.

In the statement made by the authors that "The field-capacity represents the approximate upper limit of moisture-content which can be stored in a soil for use by plants under field-conditions", qualification is made regarding the field-capacity without doing the same for plants. Plants such as rice, willows, etc., under field-conditions, can make use of water above field-capacity.

The discussion regarding the contribution to underground basins is pertinent. Many people attribute a rise in the measured water-table that takes place during the non-pumping season to recent contribution from surface-sources, when in reality it might mean that water has moved downward from the saturated, fine-textured soils that are being unwatered by a falling water-table.

O. W. ISRAELSEN, Utah State Agricultural College--The authors are commended on the presentation of an interesting and valuable article. It is true, no doubt that the most helpful conception of soil-moisture phenomena may be gained by a consideration of energy-relations.

Thirty years have passed since Buckingham recognized the value of the potential function in studies on the movement of soil-moisture [see 6 of references in paper under discussion]. However, its usefulness in these studies seems to have been overlooked during the decade following Buckingham's work, but it was recognized by Gardner nearly 20 years ago with the result that he and his students have made substantial progress in its application [9, 10]. In this connection, the article by Richards [see c of references at end of remarks] entitled "The usefulness of capillary potential to soil-moisture and plant-investigators" is noteworthy.

There is, perhaps, merit in the preference stated by the authors for the term "moisture-potential." The designation as either "capillary potential" or "moisture-potential" is desirable to distinguish this function from the "gravitational potential" of which the authors speak in their discussion of soil-moisture dynamics.

The authors' tentative conclusion that the soil-moisture potential is about the same for all soils at permanent wilting-moisture percentage, and likewise at field-capacity, is far-reaching and valuable. Further experimental study with a view to removing doubts and making this conclusion final should be encouraged.

In studies and measurements of the flow of water in soils, the potential function is, perhaps, of particular importance and usefulness. The fact that the Committee on the Physics of Soil-Moisture is concerned especially with unsaturated soils probably explains the exclusion of saturated soils by the authors, and their failure to mention the classical work of Darcy [a], Slichter [d], Hazen [b], and others concerning applied hydrodynamics.

It is appropriate to think of the use of the capillary potential (or the moisture-potential) in the study of the soil-moisture dynamics of unsaturated soils as an extension of the concepts and the fundamental laws of mechanics early used by Slichter [d] and others in the study of soil-water dynamics in saturated soils. In the latter it is, of course, essential to deal with positive pressures, whereas in the former negative pressures are encountered.

Combining the equations of motion with the equation of continuity for the case of steady flow due to pressure-differences with no external attractive forces, Slichter obtained the differential equation used in many branches of applied mathematics, known as Laplace's equation. He then pointed out the fact that the pressure-function, p, which satisfied Laplace's equation is called a "potential function." He also called attention to the fact that the equation of Laplace would be satisfied even if the velocity of ground-water were not directly proportional to the pressure-difference, but varied in an arithmetical progression, as then claimed by some. Slichter made the existence of the potential function the basis of his noteworthy contributions to understanding of the flow of water in saturated soils.

Brief comments follow concerning part of the authors' discussion on dynamics. It would seem more precise to use the term "unit-mass of water" instead of "particle of water." The following statement made by the authors needs amplification: "The latter force (meaning the gradient of the moisture-potential) acting on the mass of water in the soil is constant with time during the wetting process. . ."

It would seem essential that the zone of unsaturated soil at the water-front should have a depth constant with time as the water advances and that the soil-moisture potential at the lower and upper limits of the advancing zone of moist unsaturated soil must also be constant with time, in order to make the gradient of the moisture-potential constant with time during the wetting process.

These conditions, which seem to be essential to the correctness of the statement of the authors above quoted, are probably not adequately supported by the experimental data now available, despite the fact that some recent experimental data seem to support them.

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L. B. OLMSTEAD, United States Department of Agriculture, Bureau of Chemistry and Soils--Perhaps I hold about the same view that the authors do about hygroscopic, capillary, and gravitational water, but I should express it differently. To me hygroscopic water means surface-absorbed or adsorbed water. Much of the water which soils absorb from the air may be capillary water because water in the vapor-phase may enter soils either by surface-adsorption or capillary condensation. When the body forces of water exceed the capillary forces, gravitational water appears. It seems to me that these are perfectly definite concepts although of course their exact values depend upon a continuous soil-moisture curve that will vary with temperature, packing, and other factors which vary from time to time. It seems to me the difficulty is not with the classification but with the experimental determinations.

Due in part to the necessity of supercooling it has been difficult to determine the freezing-point of soils, and so far as I am aware the literature contains no melting-point data. Alexander and Shaw are working on a method for determining both freezing- and melting-points. A preliminary report was presented at the last meeting of the American Society of Agronomy.

P. J. KRAMER, Duke University--The idea that no sharp distinction need be made between free, capillary, and hygroscopic water seems to be entirely compatible with what is known of plant soil-moisture relations. The fact that the permanent wilting-percentage falls in the region of greatest curvature of the moisture-potential—soil-moisture-content curve explains why the permanent wilting-percentage is largely independent of the species of plant and climatic conditions. A small decrease in soil-moisture decreases its availability so greatly by decreasing the rate of movement from soil to root that it cannot be compensated for by any possible increase in absorbing power of the roots, such as an increase in osmotic pressure or suction-tension.

The writer believes that at higher soil-moisture contents roots can absorb water from the films surrounding the soil-particles with which they are in contact about as readily as from liquid water. This is indicated by data showing that the lag of absorption behind transpiration is no greater in plants growing in auto-irrigated soil near its moisture-equivalent than in plants growing with their roots in pure water or dilute nutrient solutions [see 2 of references at end of remarks].

The slowness with which water moves at moisture-contents usually existing in the field makes the rapid and continuous extension of the root-system of transpiring plants a vital necessity for their survival. Only by constantly coming in contact with hitherto untouched soil-particles and their surrounding films of water can enough water be obtained to replace that lost in transpiration. Furthermore, the roots of many plants are completely suberized when root-extension ceases. This writer believes that when environmental conditions favor rapid transpiration, cessation of root-extension for only one or two days would result in the death of many, and possibly most plants, from desiccation. The investigations of Pavlychenko [3] indicate that the number of growing root tips is extremely large and their extension must amount to many feet or, in the case of large plants, to hundreds of yards daily. In soils below the field-capacity this would make available large quantities of water which would never be available to static roots. Even normally growing root-systems apparently are sometimes unable to absorb water rapidly enough. It is well known, however, that corn and other crop-plants sometimes wilt on hot, clear days even when growing in soil containing an abundance of available water. The writer has observed wilting of corn and tobacco, two days after a rain, growing in soil still above the moisture-equivalent. It is suggested that perhaps this wilting is caused by the internal resistance of the roots to water-movement rather than by inability to absorb water from the soil-particles. Apparently the root-cells offer considerable resistance to water-movement as water passes through dead roots much more rapidly than through living roots with the same pressure-gradient [1].

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M. R. LEWIS AND R. A. WORK, United States Department of Agriculture, Bureau of Agricultural Engineering, respectively--The article does well to emphasize again the confusion which has arisen from the attempt to classify soil-moisture into definite forms, as hygroscopic, capillary, and gravitational. In another way this over-simplification of the plant-soil-water complex has led to trouble. Soil-moisture conditions have been considered as static whereas in the root-zone of a growing crop static conditions can never exist.

The dynamic nature of the problem is shown by the suffering of trees at higher soil-moisture conditions on days of high transpiration-opportunity than on moister or cooler days [see 2 of references at end of remarks]. While there is as yet no proof that the soil in immediate contact with some or all of the roots may not have reached the wilting range, experiments at Medford [1, 4, 5, 6] have shown that in heavy clay-soils pear trees may suffer, as shown by decreased rate of growth of wood and fruit and shorter periods of stomatal opening and by tree-wilting, before the moisture-content of any considerable portion of the root-zone has approached the wilting percentage. The term "stress-point" has been suggested [3] to designate the soil-moisture content at which a particular plant or crop would begin to suffer for water at a particular time. It is emphasized that the value of the "stress-point" will vary with the soil, the variety of plant, the root-top ratio of the plant, the conditions of weather, and, probably, other factors.

Both results secured in pear-irrigation studies at Medford and logical deduction from known facts make it difficult to believe that under usual growing conditions roots will withdraw moisture at a uniform rate as the moisture-content of the soil-mass is reduced from the field-capacity to the permanent wilting-percentage. Roots are not found in intimate contact with all parts of the soil even in zones of most concentrated root-growth. It is known that plants cannot withdraw moisture much below the permanent wilting-percentage and that movement of moisture in response to moisture-potential gradients in this range is very slow. Even if it be assumed that roots can extract water from soil in immediate contact as readily at the permanent wilting-percentage as at the field-capacity, the movement of moisture from soil-particles at a distance (perhaps only a few millimeters) must slow up as the moisture-content is reduced. Whether the result of this slowing up will be negligible, as seems to be the case in the California work, or easily measurable, as in the Medford studies, appears to be largely a question of the adequacy of the root-system of the plant as related to its transpiring power.

Plant-soil-water relations are of practical importance almost exclusively in the region between field-capacity at a potential of about 1×10^6 ergs per gram and the wilting point at a potential of less than 20×10^6 ergs per gram. This is just the region in which measurements of the potential have been least satisfactory. Nevertheless, the study of energy-relations seems essential to complete understanding of the problem.

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L. A. RICHARDS, Iowa State College--The paper entitled "Interpretation of soil-moisture problems by means of energy-changes" is of particular interest to me and I am in complete agreement with the authors in emphasizing the continuity which exists in the physical properties of water in soil as the moisture-content is changed. I also feel there is much to be gained by interpreting soil-moisture phenomena in terms of energy-relations. At present, however, confusion is invited by the fact that there is little uniformity regarding definitions or choice of symbols for the energy-potentials which are used in connection with soil-moisture.

Interpreting Buckingham's (see 1 of references at end of remarks) definition of the capillary potential function ψ in the broadest sense would make it equivalent to the negative sum of Linford's [2] pressure π and osmotic ω potentials. But the method suggested by Buckingham for measuring ψ, as well as Gardner's porous cell-vacuum gage combination, can be used to measure π only. In some of my papers [3, 4] I have considered the capillary potential equal to the pressure-potential. In the paragraph following the authors' defining equations for ψ they apparently identify their "moisture-potential" with the pressure-potential. I feel this may be unwise since from their article I infer it is their intention to have the "moisture-potential" measure all energy-changes in soil-water. The pressure-potential is defined only for the liquid phase and, when referred to a flat, pure-water surface, cannot be evaluated from vapor-pressure or freezing-point measurements without correcting for the osmotic potential.

Some time ago I pointed out [3] that the free energy is a function which can be used for expressing the energy-changes of water over the entire range of conditions found in soil. Although very closely related to the mechanical potential the authors suggest, it would seem to me the thermodynamic function is better suited for general use in work on soils. Schofield [5] and more recently Alexander and Haring [6] have made use of the free-energy equations. Unfortunately, the free energy, like the vapor-pressure, changes slowly with soil-moisture content in the plant-growth range. Schofield's pF-scale for the free energy largely overcomes this difficulty and should prove useful. Alexander and Haring have given the curves for four soils showing the relation between moisture-content and the free-energy change expressed in calories per gram. Gardner [7], fifteen years earlier, shrewdly guessed the form of these curves.

The authors state "The accuracy of the measurements now available justifies the assumption of a linear relation for the major part of the curves." I may be missing the point they had in mind, but I cannot see that this approximation is justifiable or helpful.

Alexander has greatly improved the technique of the freezing-point method by observing changes in the dielectric constant of the water on solidification or melting. This paper was given at the Agronomy meeting in November and will be published, I suppose, in the forthcoming Proceedings of the Soil Science Society of America.

I agree with the authors that the problem of deriving the potential in centrifuged soil has not been solved. The method of calculation used by Schofield does not give results which agree with the experiment.

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L. K. SHERMAN, Chairman, Section of Hydrology, American Geophysical Union--All of my studies and investigations on the subject-matter have related to infiltration of rainfall, or movement of ground-water to the soil. It is interesting to note how all of these different scientific phases correlate when they are approached from radically different angles.

In "Civil Engineering," published by the American Society of Civil Engineers for July, 1933 (p. 391), D. P. Barnes reports on experiments of permeability of soils. Two very important features of these experiments, made in a laboratory in Berlin, attracted my attention. One of them is as follows: "Temperature has been found to be an important factor. A rise of a few degrees in the daily average has caused the lapse of time between the 'rain' and the discharge to be shortened from weeks to days." I wonder whether other observers have noted this phenomenon. May the temperature-effect in this case be due to the artificial conditions in the laboratory wherein the soil is placed in a metal box two by two feet and about six feet long? Of course, we know that there is much greater infiltration during the summer, but I had accounted for this by increased evaporation.

C. A. TAYLOR, United States Department of Agriculture, Bureau of Agricultural Engineering--A helpful presentation is made in this paper on soil-moisture problems. The curves in Figure 1 are of particular value in providing a picture of energy-changes over the ordinary range of soil-moisture variations. An inspection of these curves shows why the wilting range may be expected to extend over a greater range of moisture-contents in clays than in sands.

Citrus trees are often irrigated so that the entire root-zone is not moistened at each irrigation. The moisture-content of the soil in the unirrigated portions of the root-zone thus has an opportunity to come to equilibrium with the forces developed in the tree. The minimum moisture-content reached in the unirrigated portions depends on the degree of water-deficit. The range in soil-moisture between that where trees are maintained with only slight water-deficit by frequent irrigations of some fraction of the root-zone to that where trees are allowed to wilt may be as much as four per cent in moisture-content for clay soils. The range for lighter soils is less. This is to be expected according to Figure 1 of the paper. This range might conceivably extend over the region of greatest curvature of the potential—soil-moisture curves.

In irrigation practice where trees are maintained with different degrees of water-deficit, we have found the term wilting-range to be helpful in interpreting soil-moisture problems [1, 2]. Sharp distinctions are thereby avoided.

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H. A. WADSWORTH, University of Hawaii--The continued and extended use of curves showing the relations between soil-moisture content and some function of energy prompts the query, perhaps premature at this time, as to how fixed these relations are. Preliminary work with Hawaiian soils indicates that the position of the point on the energy-axis (as determined by freezing-point depressions) depends not only upon the gross soil-moisture content but also upon the drying history of the soil prior to the freezing. Using the pF-convention [see 4 of references at end of remarks], it appears that at a given gross soil-moisture percentage the pF of soils dried slowly is consistently greater than that noted when the soil is dried rapidly.

As has been indicated, the results of many workers indicate that energy is a continuous function of soil-moisture. But it is not clear that the energy-moisture curve is anything more than the composite of several curves in the same coordinates. Considerable recent work suggests the soil-moisture may be in at least two distinct forms; it is hardly logical to assume that each of them would exhibit the same energy-relations. For example, Alexander and Haring [1] aid in reviving the old conception of hygroscopic water, Nagelschmidt [3] suggests that some water may be added to or withdrawn from the crystal lattice in montmorillonite, and Bradfield [2] distinguishes between capillary and non-capillary pores. With a technique which provides time for perfect equilibrium between these suggested forms of water, the energy-moisture curve is a reliable expression. Apparently such equilibria have not been secured with the Hawaiian soils which have been subjected to local freezing-point studies. Considerable additional work on the internal energy-relations of a soil is indicated.

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L. C. WHEETING, Washington State College--Within the range of soil-moisture, which extends from oven-dry soil on the one hand to the field moisture-capacity on the other, there appears to be at least two zones in which the energy-factors responsible for the attachment of the water to and the retention of the water by the soil-particles are apparently different. The most satisfactory conception of this difference may be obtained by considering the environment in which the molecular forces are active in each zone. Beginning with dry soil and adding small increments of water, the first zone is dominated by those molecular forces which are active at the solid-liquid interface which is located at the surface of the soil-particles. Since the surface-tension of a solid material like quartz is estimated to be of the order of 1000 dynes/cm^2 [see 2 of references at end of remarks], the force with which a molecule of a liquid such as water is held at a solid-liquid interface is appreciable and undoubtedly results in compression and orientation of the water as indicated by the development of heats of wetting. There is a marked specificity among solid surfaces because not all of them yield a heat of wetting in water. Lead-sulphate powder gives no heat of wetting in water [5] because it apparently has no attraction for water molecules. The higher the SiO_2-content of a soil-colloid, the greater the attraction seems to be for water [3]. It seems clear that the molecular forces at the solid-liquid interface must dominate the soil-moisture as long as the thickness of the water-layer does not exceed the maximum extent of the fields of force of the molecules of the solid surface. Static friction measurements [6] indicate that the water dominated by the energy of the solid-liquid interface is composed of oriented molecules, which resist distortion and are capable of "seizing" [4]. The static friction rises as the water-film becomes more continuous through added increments. When a point is reached near the wilting point, the resistance to distortion decreases and further additions of water reduce the coefficient of static friction. It must be at this point in the soil-moisture scale that the molecular forces of the solid-liquid interface are satisfied, no more compression and orientation occurs, and the soil-moisture henceforth behaves like a fluid. Plasticity in clays becomes apparent at this point. Vapor-pressure studies [1] in moist soils support the idea that free fluidity begins as the moisture-percentage rises to the wilting point. This is the threshold of the second zone in which the fluid properties of the soil-moisture dominate. Uniform surface tension at the air-water interface developing normal vapor-pressures over a wide range of moisture, and free capillary phenomena are attributes of the soil-moisture within this zone. The water-holding power of the soil in the field is largely a matter of liquid surface-tension and angular forces, limited by the quantity of pore-space. It is this zone which is of especial significance to plants and these relationships are well covered by the authors in the present publication.

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F. J. VEIHMEYER AND N. E. EDLEFSEN, University of California--The moisture-potential, as we have used it in the paper, includes the osmotic potential as well as the capillary or pressure-potential. The osmotic potential is, however, very small in soils as compared with the capillary or pressure-potential over most moisture-contents met with in the field. The porous-cup method measures the capillary or pressure-potential only. Vapor-pressure, freezing-point, and dilatometer-methods theoretically measure the moisture-potential as we have used it. Obviously these potentials are functions of factors other than the moisture-density. They depend upon the nature of the soil, the temperature, and possibly to a minor extent upon other factors. If the porous-cup method is used to measure the moisture-potential, the suitable correction must be made for the osmotic concentration but, as pointed out above, this is usually small.

The question was raised as to the legitimacy of the approximations made in the paper that the potential—moisture-content curve may be regarded as linear between the field-capacity and the permanent wilting-percentage. This is certainly not the case, strictly speaking, but for certain purposes is probably satisfactory. Plant-behavior seems not to be influenced by variations in potential over this range, which indicates that the curves are somewhat flat and nearly linear. All measurements by physical methods available show only slight slope over this range as compared with the curve at moisture-contents lower than the permanent wilting-percentage. The portion of the curve that can be measured by the porous-cup method shows considerable departure from linearity when considered by itself; but when considered with the remainder of the curve, the departure from linearity is not striking.

The assumption made is also very convenient in mathematical analysis of problems. It must be made with caution. The problem at hand would, of course, dictate as to the legitimacy of the assumption in any particular case.

Question was also raised as to whether the gradient of the moisture-potential, at an advancing water-front experienced when irrigation water is applied to a soil, could be regarded as constant. This is an approximation, of course, but is probably not far from the truth. Sufficient information, unfortunately, is not available on this point to answer the question satisfactorily.

In the discussion attention was called to the fact that at very low moisture-contents the water held in the crystal lattice seems to produce discontinuities in the curve of potential versus moisture-content. There may be abrupt changes in curvature at some very low moisture-contents. Whether these represent discontinuities is probably questionable. These are, as pointed out, at very much lower moisture-contents than those ordinarily met with in the field.

In the discussion several called attention to the pF-scale introduced by Schofield. This is considered by some to be convenient in showing results graphically; but, of course, does not overcome any difficulty in making measurements from which the potential-function can be calculated over the soil-moisture content in the plant-growth range.

In calculating the amount of energy per unit-mass required to remove water from the soil it is clear that the reference-point must be kept in mind. If infinite dispersion is used as the base, the answer, of course, will be much greater than if a free water-surface is used.

As pointed out in the paper, no technique has been worked out whereby the potential can be measured by the centrifuge method, although it has possibilities. The potential at field-capacity is sometimes assumed to be numerically equal to the pressure in dynes per square centimeter, due to one atmosphere. This is also approximately numerically equal to the dynes per gram acting on the water in a centrifuge when subjected to a force of one thousand times gravity. There seems to be no physical reason why the potential at field-capacity should be numerically equal to these values.

In drawing conclusions as to the behavior of plants under different moisture-conditions, caution must be exercised in generalizing from results obtained under peculiar conditions. Of course, it is extremely valuable to point out apparent exceptions to generalizations. The fact that Anjou pears on a particular heavy clay-soil seem to behave differently than do pears and many other kinds of plants on different kinds of soils, including heavy clays, does not make it logical to assume that under usual growing conditions roots will not withdraw water at a uniform rate as the moisture-content of the soil-mass is reduced from the field-capacity to the permanent wilting-percentage. The explanation of this apparent exception probably is, as pointed out by the investigators who have observed them, due to the fact that the usual method of measuring the soil-moisture content does not give the actual moisture-content of the soil in contact with the roots.

The question has been raised whether it is possible to gain satisfactory pictures of plant-absorption without considering rate of water-movement instead of "static" pressures, potentials, and suctions. Similar objections would not be raised against the reasoning used in hydraulics of pipe-line flow where pressures and potentials are measured and rates of flow calculated from them. Certainly, pressures and potentials are the bases for analyzing problems in dynamics of fluids.

REPORT OF THE COMMITTEE ON UNDERGROUND WATERS, 1936-37

D. G. Thompson, Chairman

In accordance with the by-laws of the Section, the Committee on Underground Waters has been reconstituted during the past year. With their research interests turning to other subjects, several members have dropped out, and four new men have been appointed. In order to maintain contact with the work of related committees, Charles H. Lee, Chairman of the Committee on Absorption and Transpiration, and C. S. Howard, Chairman of the Committee on Chemistry of Natural Waters, have become members of the Committee on Underground Waters. The personnel of the Committee is as follows:

H. F. Blaney
G. M. Fair
Willard Gardner
C. S. Howard
F. H. Lahee
C. H. Lee
M. M. Leighton
O. E. Meinzer
A. M. Piper
H. E. Simpson
A. C. Swinnerton
D. G. Thompson, Chairman

In accordance with the action of the Executive Committee, there is included as Appendix A of this report, a bibliography of the more important recent publications of the field covered by the Committee. This bibliography was prepared by A. N. Sayre. Numbers in brackets in the present report refer to the corresponding number of titles in the bibliography. The bibliography will serve largely as the Committee's contribution to the International Bibliography on Hydrology. Attention is called to the fact that many articles of more local or minor hydrologic interest are listed in several abstract magazines or sections of magazines which cover the subject in a satisfactory manner. Probably the most comprehensive of these, so far as the many phases of ground-water hydrology are concerned, is the Annotated Bibliography of Economic Geology. Others include the Journal of the American Water Works Association, Civil Engineering, Public Works, Engineering News-Record, and Water and Water Engineering (English). The International Bibliography will be a welcome addition to this list in so far as it covers the foreign countries.

With another summer of severe drought just passed, interest continues to focus on fluctuations of ground-water levels. Two events stand out on this subject. One was the issuance for the first time of weekly statements prepared by the United States Geological Survey in regard to general ground-water levels in drought-stricken states. The other is the publication of United States Geological Survey Water-Supply Paper 777 [42], which is the first of an annual series to give available records of ground-water fluctuations obtained by the Survey. The report includes measurements from 24 states and the Territory of Hawaii. In several states the observation-wells are scattered over wide areas, representing a great variety of conditions, but in some states they are confined to areas of heavy pumping. For many of the wells the records of past years are published, and the second volume of the series, now in course of preparation, will publish back records for many more wells.

Perhaps just as significant as the drought, but less well advertised so far as observations of ground-water level are concerned, is the fact that the past year, or a little longer period, has been one of great floods. Just as a very few years ago it was suddenly realized that there was a scarcity of adequate records showing the effects of severe droughts on ground-water levels, now it seems that there are not many observations to show the effect of unusually heavy precipitation that produces floods. Surely we need to know as much about the possibilities of recharge following a period of drought as we do about the actualities of low ground-water level during the period. A few examples of the vagaries of Mother Nature along this line may be cited. In Pennsylvania, as described in a paper by S. W. Lohman at a session of the present meeting, during the record-breaking flood-period in the spring of 1936, the water-levels reached a higher average stage than at any time in six years of observation; but shortly thereafter there occurred a decline which exceeded in length and rapidity that of any of the previous years, and the lowest level reached was about as low as in any of the preceding years of observation, which included years of deficient precipitation. In Mill Creek Valley, near Cincinnati, during the past year the water-level in many wells reached lower stages than at any time during some 30 years of measurements at irregular intervals. Subsequently, following the heavy precipitation that produced the great Ohio River Flood of January and February of the present year, the water-level in some wells rose 10 to 15 feet, to levels higher than any in at least six years. On the other hand, some wells in the same area showed very little rise in level. In Nebraska, during the past summer, the drought carried the curve of accumulated departure from normal precipitation to a point an accumulated deficiency, in some 60 years of record, several inches greater than the previous greatest deficiency points (reach successively in 1934 and 1935). In spite of this fact, the water-level in most observation-wells throughout the State did not drop as low as in 1934, apparently because of satisfactory precipitation and recharge in 1935 as compared to considerably deficient precipitation and recharge in three of the four years prior to 1934. These examples help to emphasize to the layman the fact which is well realized by hydrologists that infiltration and recharge as evidenced by fluctuations of the water-table are indeed complicated phenomena. Some phases of these phenomena are well brought out in the symposium of the present meeting, and by the paper by R. E. Horton on the subject of "Surface-runoff control" and the discussion of that paper, presented September 23, 1936, at the Upstream Engineering Conference [24].

Among other studies of changes in ground-water head, mention may be made of a Works Project Administration project under the auspices of the South Dakota State Planning Board, the results of which have been published recently in a 138-page mimeographed report entitled "Artesian-well flow in South Dakota." The report states that the records of 11,229 artesian wells, constituting about 75 per cent of the estimated total of 15,000 such wells in the State, were analyzed. Of these, about 35 per cent have stopped flowing, about 45 per cent have shown a decrease in flow, and about 20 per cent still have a "strong flow." For each of 40 counties there is given a map showing the location of wells in the above groups, graphs representing similar percentages for the county, and the trend in number of wells and average flow in 1912, 1922, and subsequent years ranging from 1926 to 1932. Unfortunately, little or no definite information is given on changes in head. Inasmuch as a decrease in the flow of a well may result from stoppage of casing, or leaks in it, without any actual decline in head, the data in regard to changes in flow alone may not be significant in indicating changes in artesian head. Observations of 56 wasteful wells, 36 of which were classified as "wild," showed a total flow of more than 11,000 gallons a minute, and it was estimated that the waste from the 56 wells alone would support 11 times as many head of cattle as were shown by the Federal Census of 1935 to be on the farms in the area studied. The report contains much valuable information of a statistical nature, but obviously does not attack certain fundamental geologic and hydrologic problems, the solution of which is essential to a determination of the ultimate safe yield of the artesian aquifers.

In view of the value of the great Dakota formation as an artesian aquifer in South Dakota and other states of the Great Plains, and of the information showing early high pressures and subsequent great decline in pressure, it is unfortunate from both the practical and the scientific standpoints that continuing systematic observations have not been maintained on many artesian wells in this area.

George S. Knapp, Chief Engineer of the Division of Water Resources, Kansas State Board of Agriculture, reports that observations of ground-water levels in southwestern Kansas have been made for comparison with the water-levels reported by E. S. Nettleton about 1890. The results of this study will be awaited with interest.

Dr. M. M. Leighton reports that the Illinois Geological Survey has made plans to study the static water-levels in the deep formations of the Chicago area. Dr. Leighton has also forwarded the following information in regard to observations of ground-water level along the Mississippi River by two districts of the United States Engineer Office of the War Department.

The United States Engineer Office at Rock Island, Illinois, reports as follows for the portion of the Mississippi River Basin north of Hamburg Bay:

"The ground-water observation-wells in which this office has a direct interest are located in the bottom lands along the Mississippi River and are, for the most part, comparatively shallow, varying from 8 to 20 feet in depth. There are 54 permanent ground-water gages which penetrate to an average depth of about 16 feet. These gages are read daily and extend over territories between Guttenburg, Iowa, and Clarksville, Missouri. Forty-seven of these gages were established during the period 1931-32, the balance having been added to date. Daily readings on these gages are submitted monthly, by paid gage-readers, to this Office. During the summer of 1935, about 230 additional, but less permanent, ground-water gages were established along the valley of the River between a point just upstream from Savanna, Illinois, and Louisiana, Missouri. In addition, about 20 more of the semi-permanent gages were installed during 1936 in the same region. These gages are open pipes about eight feet in length and have been installed in connection with the preparation of a special report called for by the Rivers and Harbors Committee, Congress of the United States. The water-surface elevations in these wells are determined intermittently by field-survey parties.

"In addition to these wells, 95 open-ditch staff-gages have been set and are being read intermittently by field-survey parties.

"Further, 182 gages have been installed in open pools and lakes in the bottom lands. As above, these gages are also read intermittently by field-survey parties."

The United States Engineer Office at St. Louis reports as follows:

"We have no wells in drainage-districts in Illinois, except those along the Illinois River. In the State of Missouri two levee-districts are under observation: The Elsberry Drainage-District, with a length of about 14 miles and an area of 23,480 acres, the center of which is about opposite Hamburg, Illinois, and the Kings Lake Drainage-District, about five miles long with an area of 3366 acres, which is near Oasis Station in Missouri and adjoins the southern end of the Elsberry District. The purpose of the wells is to determine elevations of the water-table for various river-stages and after rain-storms.

"There are 73 observation-wells in the Elsberry District, spaced more or less regularly but in such fashion that approximately all known surface and near-surface soil-conformations in the District are penetrated. The wells consist of 2-5/16 inch black iron pipes open at the bottom and perforated, except for the top four feet, with 3/16-inch diameter holes, on six-inch centers. Sixty-one of the pipes are set at a seven-foot depth and 12 of them at a 20-foot depth. Water-surface elevations are normally read twice a week and oftener when river-stages are at high or low extremes.

"In the Kings Lake District there are six wells having a seven-foot depth and placed irregularly in the District; they are read only at selected periods.

"Soil-borings were made at each of the wells to a depth that penetrated the porous stratum. Field-classification was made of the various strata encountered and at a later date mechanical analyses were made in the laboratory for some of the soil-samples.

"The duration of this program is uncertain but will probably be of sufficient length to determine certain limits of water-table oscillation."

The United States Engineer Office at St. Louis also reports on ground-water observations along the Illinois River as follows:

"The jurisdiction of this Office over levee-districts along the Illinois River extends from the mouth to Havana, Illinois; the remainder of the stream is under the District Engineer at Chicago.

"Observation-wells have been placed in eight levee-districts for the purpose of obtaining ground-water elevations under various conditions of river-stage, rainfall, pumping, etc. The data are being collected for a report to Congress and are not available for general use until the report has been printed."

The statement contains an annotated list, by levee- and drainage-districts, which includes a total of 105 wells, apparently all being on the lowlands along the River. The wells range in depth from 7 to 26 feet, and observations have covered periods of different length from 1932 to the present time.

Mention should be made of the recommendation of the Water Resources Committee of the National Resources Committee, in its report on "Deficiencies in basic hydrologic data (April 18, 1936)" of a program for the construction and observation of some 10,000 observation-wells to be distributed throughout the country, at an estimated cost of $700,000 by the Federal Government and $300,000 by states or other non-Federal agencies in the first two years, and thereafter $212,500 annually by the Federal Government and $112,500 by non-Federal agencies.

It is just as important, economically and scientifically, to have continuous observations of fluctuations of ground-water level in times of flood and normal precipitation and ground-water supply as in times of drought. In order that the effect of deficiencies of ground-water may be understood and interpreted, normal conditions and their effects must be known. Even during periods of abundant ground-water the supply for power and for other purposes may be definitely relied on only if records are at hand on which to base estimates of the supply available.

Along the line of infiltration and ground-water recharge, Harry F. Blaney reports the following activities of the Division of Irrigation of the United States Department of Agriculture, Bureau of Agricultural Engineering:

"The Bureau of Agricultural Engineering of the United States Department of Agriculture has been conducting a series of tests in southern California since 1930, leading to determination of influences of various factors affecting rates of percolation, and consequently the efficiency of the several methods of artificially recharging depleted underground water-supplies by spreading flood-waters over absorptive areas.

"Although a manuscript entitled 'Spreading water for storage underground' has been submitted for publication, these experimental plots are being maintained for further study.

"The principal influencing factors considered in this study include percolating, efficiency of various soil-types, effect of temperature, topography, surface-soil treatment, use of silty water, whether the surface should be denuded or in native vegetation, fluctuation of underground water-levels, and other contributing influences.

"The Bureau has also been studying the efficiency of recharging underground supplies by means of wells and shafts. The results up to the close of the 1935-36 spreading-season are included in the manuscript referred to above.

"The Bureau of Agricultural Engineering, in cooperation with the Bureau of Plant Industry, has been observing ground-water conditions of the Bard Area in the vicinity of the All-American Canal.

"These investigations were started two years ago when ground-water levels were about normal, and before water is turned into the All-American Canal. Recording equipment with 14-inch and 30-inch floats are installed in 36-inch wells to register the fluctuations of the water-levels as affected by surface-irrigations, canal and river-losses, and by the withdrawal of soil-moisture by plant-transpiration. These wells are known as key-wells and are used in conjunction with the ordinary iron-pipe, strainer-equipped, observation-wells. Samples of ground-water and river-water are obtained frequently for salinity-tests, and used to assist in determining the source of underground water, and for other purposes.

"Upon completion of Boulder Dam and the storage of irrigation water in Lake Mead, the water released is clear and in its passage from the Dam to the points of diversion for irrigation use picks up only a part of the original silt-load. Consequently, when the clearer water is applied to the irrigated areas, the rates of percolation are higher, and the contribution to the underground supply greater. The controlled water at Boulder Dam also prevents large flood-flows, and as a consequence native river-vegetation is growing rapidly on areas formerly occupied by the river-channel.

"The particular object of these investigations is to determine the rate of rise of the underground waters, source of underground water, salinity-variations, and the effect of these factors on crops grown in this area."

Blaney also reports that the Bureau of Agricultural Engineering is participating in ground-water investigations in both South Dakota and North Dakota, which will involve the collection of data as to the present position of the water-table.

In many localities in the past few years there has been a great increase in the use of ground-water for air-conditioning. In fact, there is a possibility that in some localities the great use of water for this purpose may produce serious problems of overdraft before the conditions become dangerously apparent and remedial measures can be taken. The Division of Marketing Statistics, United States Department of Commerce, has undertaken a study of this problem and has sent out a questionnaire to determine the extent to which consumption of water for air-conditioning has increased. Also, in connection with this problem, the United States Geological Survey in cooperation with State and County agencies is making a study of the fluctuation of temperature of ground-water on Long Island where, under State regulation, ground-water used for air-conditioning is returned to the ground. Along the same line, but less definitely related to problems of air-conditioning, are observations made by the United States Geological Survey in cooperation with the Nebraska Conservation and Survey Division to determine fluctuations of the temperature of water from both deep and shallow wells. These have shown surprising changes in temperature of the water from winter to summer. Ground-water hydrologists will also be interested in recent developments in the use of thermometric measurements in oil-wells to distinguish between different strata, to determine top of cement around casing, etc. [32]. One may wonder whether such measurements may be found to be useful in hydrologic studies.

There is increasing use of the electrical-resistivity methods in ground-water studies. The results of several studies are reported in papers on another partof the present program. Other phases of the use of this method--as applied to ground-water and other investigations--were presented in several papers at the February meeting of the American Institute of Mining and Metallurgical Engineers.

A phase of ground-water hydrology that finds its way into the program of the Section of Hydrology for the first time is the quantity of water encountered in mining operations, as described specifically for the Pennsylvania anthracite region, by D. C. Ashmeade. It is to be hoped that more information on this subject may be forthcoming for other areas. Along the same line the very useful work of closing openings of abandoned mines to reduce the acid content of waters discharged therefrom is covered in the report of the Committee on Chemistry of Natural Waters.

In the report of this Committee for 1934 attention was called to a subsidence of the land in Santa Clara Valley, California (Howard S. Rappleye, Eng. News-Rec., v. 110, p. 845, June 29, 1933) and the suggestion of Fred H. Tibbets (Eng. News-Rec., v. 111, p. 204, August 17, 1933) that the subsidence may be due to a lowering of the water-level as a result of heavy pumping from wells. Recent releveling by the United States Coast and Geodetic Survey reveals that this subsidence has now reached five feet [60]. The recent statement does not specifically consider causes of the subsidence. However, the author reports the significant fact that as it has progressed the tops of many well-casings have protruded to greater and greater heights above the ground-surface, in some instances raising the heavy pumps with them. This indicates that the lower beds, at a depth of about 800 feet, in which the wells are set have not been affected as greatly as the shallower beds, and lends support to the suggestion of Tibbets.

There are a number of other areas in the United States where there has been a great decline in hydrostatic head, and it would be desirable to relevel these areas to determine whether subsidence has occurred in them. Among these areas are: Houston, Texas; Chicago area where the artesian head has declined 300 feet, or more; parts of the great Dakota artesian basin, in some parts of which the decline in head has also been as much as 300 feet; and Atlantic City region, where in places the head on the 800-foot sand is about 100 feet below its original level. O. E. Meinzer suggests that it will also be instructive to ascertain whether any rise of the surface is caused by introducing water under pressure, as in the Bradford Oil-Field of Pennsylvania.

The compressibility of water-bearing formations and related phenomena of elasticity and lag in response to changes in pumpage is especially worthy of consideration in the Atlantic City Region where ten years of more or less detailed observations on fluctuations of head and pumpage are now available. The results are described in a recently issued report by H. C. Barksdale, R. W. Sundstrom, and M. S. Brunstein [4]. This report discusses a new concept in ground-water hydrology, regional specific capacity, which is comparable to the specific capacity of a single well, but is based on the change in head over a whole region for changes in the pumpage from the entire region. On the basis of records for ten years in the Atlantic City Region there is indication that there has been a more or less progressive decline in the regional specific capacity of the 800-foot formation. The true significance of this has not yet been determined but it may be in part due to the compression of the formation.

R. M. Leggette reports preliminary results of observations on the fluctuations of water-level produced by trains moving past an observation-well. Records have been obtained with automatic recorders modified to give greatly enlarged vertical and time-scales and these give promise of a valuable approach to a more detailed study of the problem of compressibility.

The report on the Atlantic City Region mentioned above contains much valuable information in regard to other ground-water problems, of both a practical and scientific nature. These include a comparison of fluctuations of head and pumpage in a well-field from which the water formerly was taken from many closely spaced wells of small diameter and now is pumped from a few widely-spaced wells of large diameter. The report also describes detailed studies of the contamination of shallow water-bearing formations by salt water, in which many test-wells were drilled in such a way that samples of water were obtained from different depths for determinations of chloride. Studies of the problem of salt-water contamination on Long Island are also being continued by the United States Geological Survey in cooperation with State, County, and municipal agencies.

A. M. Piper has reported the following ground-water activities in northwestern states:

"In Oregon, the United States Geological Survey and the State Water Resources Department are cooperating in monthly measurements of spring-flow and of water-levels in a group of observation-wells in the Walla Walla Basin, also in occasional measurements of water-level in a few representative wells in four other ground-water districts. The United States Engineer Department has discontinued its program of water-level measurements in wells of the Willamette Valley. The United States Soil Conservation Service has continued its determinations of fluctuations in ground-water level in relation to rainfall, runoff, and infiltration at the experimental area near Athena, in Umatilla County. Also has recently established other experimental areas near Morrow and near Forest Grove and contemplates similar hydrologic studies there. In Washington, the Soil Conservation Service has continued its hydrologic studies on the experimental area near Pullman (the area includes a part of Idaho).

"In Idaho, the United States Bureau of Reclamation is continuing its study of water-supplies for irrigation in the Snake River Basin. This study involves some work on ground-water conditions."

C. E. Ramser has furnished the following statement of ground-water studies being conducted by the United States Soil Conservation Service:

"In cooperation with the State experiment stations and as a part of the Soil Conservation Service's research-program, it is planned to establish experimental watersheds, of approximately 5000 acres in size, in various parts of the country. Two such watersheds have been established, one located near Coshocton, Ohio, and one near Waco, Texas, while others are now being selected.

"It is planned to measure precipitation on the watersheds by the installation of standard and recording Weather Bureau rain- and snow-gages. Topographic, erosion, geologic and ground-water, and land-use surveys are to be made periodically. The disposal of precipitation will be accounted for, as nearly as possible, by measuring rates and amounts of surface-runoff, evaporation, infiltration, transpiration, stem-flow, and interception, and by determining the amounts of soil-moisture and ground-water storage.

"The objective of the ground-water studies on the experimental watersheds will be to determine the effect of improved land-use and erosion-control practices on the level of the ground-water. The location and type of observation-wells used will necessarily differ in different localities and will be dependent on the findings of a preliminary geological survey of each experimental watershed. Observations on the level of the ground-water at the observation-wells will be both manual and automatic, although it is planned to equip as many such wells as possible with automatic stage-recorders.

"All well-records will be studied and analyzed with respect to such supporting data as rainfall, surface-runoff, soil-moisture, and land-use. Hydrographs showing the fluctuations of the water-table at each well, moving averages of such fluctuations, and cross-sections to show the shape and fluctuations of the water-table, will be plotted.

"As a result of the above observations and analyses, future ground-water studies will be outlined. Such studies will have for their immediate objective the quantitative estimate of the changes in ground-water storage and will include underflow-studies, as well as the determination of such factors as specific yield, porosity, specific retention, and permeability of the materials in which the ground-water is found to exist.

"On the Coshocton project, 31 observation-wells have been completed and five additional wells are now under construction. Fifteen hundred auger holes were made to an average depth of four to five feet, in a study of geologic formations and soil-depth. Manual ground-water measurements at completed wells were begun May, 1936.

"On the Waco project, 128 auger holes were drilled to an average depth of 20 to 25 feet in a preliminary geological survey of the watershed. A number of these auger holes have been cased with steel casing and are to be used as observation-wells. 'It is planned to case additional holes or to drill as many additional wells as may be found necessary to the correct interpretation of the data."

Morris Muskat has communicated the following information in regard to studies of the Gulf Research and Development Corporation that may be of interest to hydrologists:

"As you may recall from my letter of last year, we were then completing 'left-overs' in our studies of strictly honogeneous fluid-flow systems and had definitely turned our interest toward the flow of gas-liquid mixtures. The first results of this work have beenpublished as two papers in Physics, namely, one by R. D. Wyckoff and H. G. Botset [7] and the other by M. Muskat and M. W. Meres [44]. While we believe this work to be a necessary preliminary for the further study of gas-liquid mixture systems, we make no pretense with regard to its direct applicability to ordinary hydrological problems. Likewise our study of the infiltration of mud-particles into porous sandstones, which will be published in the April issue of the Journal of Applied Physics, by Dr. W. N. Arnquist, is another example of our work which might well be of general cultural interest to a hydrologist, but yet could lay no claim to being of professional interest to him. I am afraid therefore that our own activities are definitely tending to enter more actively into the practical petroleum-production field and to leave what is for our purposes perhaps the more academic but none the less interesting phase of homogeneous fluid-flow.

"As to a general item of interest you may or may not be aware of the activity that has recently been developing in the oil-industry with regard to the question of the presence of connate water in what have hitherto been considered to be sands fully saturated with oil. It has become common in the last several years to accept findings of research investigators that sands which have for some time been producing pipe-line oil nevertheless contain within their pores anywhere from 10 to 40 per cent of connate water. The importance of this problem to the oil-industry, especially from the point of view of estimating oil-reserves, will of course be obvious."

Dr. Muskat reports that his book on the flow of homogeneous fluid through porous media is in press and should appear within a couple of months as one of the International Physics Series of books published by the McGraw-Hill Book Company.

Professor A. C. Swinnerton has furnished the following items in regard to research on the hydrology of limestone terranes:

The National Park Service reports, through Chief of the Naturalist Division, Earl A. Trager: "A number of caves under the supervision of the National Park Service have been surveyed either by Service engineers or through cooperation with other bureaus or agencies. In general, these surveys traverse over pathways and through passages used by tourists and in most cases include profile-levels and selected cross-sections.

"Areas surveyed by the Engineering Branch of the Park Service are: Carlsbad Caverns, New Mexico; Crystal Cave in Sequoia National Park, California; Wind Cave, South Dakota; Lehman Caves, Nevada; Mammoth Cave, Kentucky; Oregon Caves, Oregon; Timpanogos Cave, Utah; and Jewel Cave, South Dakota.

"The National Geographic Society, in cooperative with the United States Geological Survey, conducted extensive surveys in Carlsbad Caverns. The Forest Service has surveyed, in part, Lehman Caves, Oregon, and Timpanogos Cave, Utah. The United States Geological Survey ran the primary traverses through Mammoth Cave, Kentucky.

"Generalized geologic statements of the formations in which the caves exist and in some cases a brief description of the cave-formations have been prepared. Sufficient research has not been done to establish the geologic sequence of events which lead to the formation of the caves.

"J. Volney Lewis has prepared a general treatise on caves for the National Park Service for use in the Service's educational and geological work. This publication is now ready for the printer."

The proposed trans-Florida sea-level ship canal has stimulated much research in ground-water circulation in that area. During the year publications by Sidney Paige [46] and Henry S. Sharpe (Science, new ser., v. 83, pp. 520-522, 1936) dealt specifically with theoretical reactions of ground-water to the proposed excavations. V. T. Stringfield's work on the artesian water of the older Floridian limestone, published in 1937 [61] is being continued by cooperation between the United States Geological Survey and the Florida Geological Survey and includes a study of the artesian and non-artesian conditions in Eocene and younger limestones. A brief report on artesian water in Florida west of the Suwannee River is being prepared.

Douglas Johnson (Science, new ser., v. 84, pp. 15-18, 1936) suggested the interesting hypothesis that the so-called meteor scars of the coastal plain of the Carolinas were the result of sink-hole development in limestones underlain by a thin veneer of younger materials. Professor Johnson writes that a book on the "Carolina Bays" is to be ready for the printer this spring (1937).

William M. McGill is continuing studies of limestone-caverns of Virginia incidental to his duties on the Virginia Geological Survey. His special interest is the formation of stalactites and Stalagmites, particularly those of the shield-type.

Edward B. Burwell, Jr., geologist of the Ohio River Division, Corps of Engineers, United States Army, is preparing to make studies of relative solubility and detailed explorations preliminary to reporting on dam-sites and reservoirs along the Ohio River.

Illness has interrupted the work which J. Harlon Bretz was completing on the origin of limestone caves.

Walter B. Lang, United States Geological Survey, who directed the investigation for potash for the Government in the Permian Basin of Texas and New Mexico, has given since 1924 such time as was available to a study of the origin of the Carlsbad Caverns. The formation of the caverns is an incidental consequence of the regional geologic events. A knowledge of the complex regional geology is essential to an interpretation of the origin of the caverns.

In the field of thermal ground-waters, a report of the United States Geological Survey on "Thermal springs of the United States" by Norah D. Stearns, H. T. Stearns, and G. A. Waring is in press as Water-Supply Paper 679-B. It includes a compilation of information in regard to about 1000 thermal springs.

During the past year, interest has been revived in the subject of the legal control of ground-water supplies by the publication of an article by Harold Conkling [11] and the extensive discussion of this paper. Another valuable paper is by G. E. P. Smith, "Ground-water law in Arizona and neighboring States" (Univ. Ariz. Technical Bull. 65, Dec., 1936). There may be a question as to the interest of the Section of Hydrology in the purely legal phases of this subject. However, without question, hydrologists do have a definite interest in seeing that, in setting up the legal principles to be followed, proper consideration be given to the scientific principles which govern the occurrence of ground-water. In Conkling's paper and some of the discussions the emphasis has been on these hydrologic principles more than in the past.

Your Chairman feels that the present report, as previous reports, has covered current work in ground-water hydrology entirely inadequately, for doubtless studies are in progress for which no information has been obtained. It is obviously impossible to report on all investigations in progress by such agencies as the Ground Water Division of the United States Geological Survey, whose programs are fully devoted to ground-water investigations, but it is desirable to note special types of studies. A survey of water-resources studies by State Geological Surveys is now being made by Dr. A. C. Tester for a Committee of the National Research Council. This should fill in some of the gaps in the present report. Your Chairman is desirous of receiving information in regard to any other investigations that have not been mentioned.

United States Geological Survey,
Washington, D. C.

APPENDIX A--A SELECTED LIST OF PAPERS RELATING TO GROUND-WATER HYDROLOGY

A. N. Sayre

In the following list, brief statements have been added to certain references to call attention to special phases of ground-water problems which are not apparent from the titles. Abstracts of most of the papers have been or will be published in the Annotated Bibliography of Economic Geology.

[1] Underground water-storage in California's south coastal basin, Eng. News-Rec., v. 115, No. 22, pp. 733-738, Nov. 28, 1935.

[2] Geological and ground-water conditions in Florida in their relation to the Atlantic-Gulf ship canal, Senate Doc. No. 147, 74th Cong., 2nd Sess., 1936.

[3] M. N. Baker and R. E. Horton, Historical development of ideas regarding the origin of springs and ground-water, Trans. Amer. Geophys. Union, pt. 2, pp. 395-400, 1936.

[4] H. C. Barksdale and others, Supplementary report on the ground-water supplies of the Atlantic City Region, New Jersey Water Policy Comm. Special Report No. 6, 139 pp., 1936. (Graphs show 10-year record of fluctuation of artesian head in 800-foot sand at Atlantic City. Computations show a decline in the "regional specific capacity" of this formation. The report gives results of detailed sampling and test-drilling to study the contamination of shallow beds by salt-water.)

[5] F. B. Blanchard and Perry Byerly, The effect of distant earthquakes on the water-level in wells, Trans. Amer. Geophys. Union, pt. 2, pp. 405-406, 1936.

[6] E. V. Boyce, Contamination of well-water supplies, Southwest Water Works J., v. 18, No. 6, pp. 11-13, 1936; abstract by O. M. Smith in Chem. Abs., v. 30, No. 21, p. 7746, 1936.

[7] Kirk Bryan, Geologic features in New England ground-water supply, New Eng. Water Works Assn. J., v. 50, pt. 2, pp. 222-228, June, 1936.

[8] Arthur Casagrande, Characteristics of cohesionless soils affecting the stability of slopes and earth-fills, Boston Soc. Civil Eng., v. 23, No. 1, Jan., 1936.

[9] T. S. Coile, Soil-samples, Soil Sci., v. 42, pp. 139-142, 1936; abstract by M. S. Anderson in Chem. Abs., v. 30, No. 21, p. 7747, 1936. (A cylinder is described which is suitable for obtaining samples of undisturbed soil for the determination of volumetric weight, air-space, and water-holding capacity.)

[10] G. E. Condra, Ground-water conditions of the shelterbelt zone, Section 14 of Possibilities of shelterbelt planting in the plains region, United States Forest Service, pp. 175-196, 1935.

[11] Harold Conkling, Administrative control of underground water--Physical and legal aspects, Amer. Soc. of Civil Eng. Proc., v. 62, pp. 485-516, April, 1936. (Discussion by Joseph Jacobs, W. D. Faucette, and J. E. Willoughby, pp. 965-969, Aug., 1936; R. E. Savage, pp. 1087-1088, Sept. 1936; H. J. F. Gomley and O. J. Baldwin, pp. 1598-1603, Dec., 1936; G. E. P. Smith and David G. Thompson, pp. 140-165, Jan., 1937; Wells A. Hutchins, pp. 323-328, Feb., 1937; John E. Field, George S. Knapp, and Chandler Davis, pp. 547-555, March, 1937; L. Standish Hall, pp. 717-718, April, 1937; Closing discussion by Harold Conkling, pp. 911-914, May, 1937.)

[12] C. W. Cooke, Geology of the Coastal Plain of South Carolina, U. S. Geol. Sur. Bull. 867, pp. 161-188, 1936. (Briefly describes the ground-water by counties in the Coastal Plain of South Carolina. Includes chemical analyses of water and records of wells together with a statement of the source of the water.)

[13] H. T. Critchlow and H. C. Barksdale, A long-term record of water level fluctuations at Plainfield, N. J., Trans. Amer. Geophys. Union, pp. 361-363, 1936. (The Plainfield-Union Water Company has made daily measurements of the water-level in a test-well at the plant during most of the period from 1891 to the present.)

[14] E. S. Cullings, Fluctuations in ground-water at Woodgate, New York, Trans. Amer. Geophys. Union, pp. 357-360, 1936.

[15] A. P. Dachnowski-Stokes, Peet land in the Pacific Coast States in relation to land- and water-resources, U. S. Dept. Agri. Misc. Pub. No. 248, Oct., 1936.

[16] F. C. Ebert, An interpretation of water-table fluctuations at four wells in southern California, Trans. Amer. Geophys. Union, pp. 371-378, 1936.

[17] A. G. Fiedler, The occurrence of ground-water with reference to contamination, J. Amer. Water Works Assn., v. 28, No. 12, pp. 1954-1962, Dec. 1936.

[18] V. M. Freeman, Water-spreading as practiced by the Santa Clara Water Conservation District, Ventura County, Calif., Trans. Amer. Geophys. Union, pp. 465-471, 1936.

[19] L. C. Graton and H. J. Fraser, Systematic packing of spheres with particular relation to porosity and permeability, J. Geol., v. 43, No. 8, pp. 785-909, 1935.

[20] Frank Heyward, Soil-sampling tubes for shallow depths, Soil Sci., v. 41, pp. 357-360, 1936; abstract by M. S. Anderson in Chem. Abs., v. 30, No. 17, p. 6106, 1936.

[21] R. A. Hill and N. D. Whitman, Percolation from surface-streams, Trans. Amer. Geophys. Union, pp. 477-478, 1936.

[22] R. E. Horton, Maximum ground-water levels, Trans. Amer. Geophys. Union, pp. 344-357, 1936.

[23] R. E. Horton, Natural stream channel-storage, Trans. Amer. Geophys. Union, pp. 406-415, 1936.

[24] R. E. Horton, Surface runoff control, in "Headwaters, control and use, papers presented at the Upstream Engineering Conference," pp. 16-41, Sept., 1936, and discussion by W. N. White, pp. 41-47, and G. S. Knapp, pp. 47-49, 1937.

[25] Paul F. Howard, Determining the yield and quality of water from tubular wells by means of the well rater and sampler, New Eng. Water Works Assn. J., v. 50, No. 2, pp. 219-221, June, 1936.

[26] M. M. Knechtel and E. W. Lohr, Ground-water in Gila and San Simon valleys, Graham County, Ariz., Dept. Interior Memorandum for Press, released Dec. 14, 1936.

[27] J. C. Kimble, Underflow at Whittier Narrows, San Gabriel River valley, Los Angeles County, Calif., Trans. Amer. Geophys. Union, pp. 521-525, 1936.

[28] Francis H. Kingsbury, Public ground-water supplies in Massachusetts, New Eng. Water Works Assn. J., v. 50, No. 2, pp. 149-196, June, 1936.

[29] D. A. Lane, Transforming surface-water into underground storage, Water Works Eng., v. 89, pp. 1136-1139, 1936.

[30] C. H. Lee, A discussion on list of terms with definitions, Amer. Geophys. Union Trans., pp. 298-302, 1936.

[31] R. M. Leggette, Long-time records of ground-water levels on Long Island, N. Y., Trans. Amer. Geophys. Union, pp. 341-344, 1936.

[32] E. G. Leonardon, The economic utility of thermometric measurements in drill-holes in connection with drilling and cementing problems, Geophysics, v. 1, pp. 115-126, Jan., 1936.

[33] Penn Livingston and T. W. Bridges, Ground-water resources of Kleberg County, Tex., U. S. Geol. Sur. Water-Supply Paper 773-D, pp. 197-232, 1936.

[34] P. P. Livingston, A. N. Sayre, and W. N. White, Water-resources of the Edwards limestone in the San Antonio Area, Texas, U. S. Geol. Sur. Water-Supply Paper 773-B, pp. 59-113, 1936.

[35] A. Loehnberg and A. Loewenstein, Electrical prospecting for water, Mining Magazine, Sept., 1936.

[36] S. W. Lohman, Geology and ground-water resources of the Elizabeth City Area, N. C., U. S. Geol. Sur. Water-Supply Paper 773-A, 57 pp., 1936.

[37] Thomas M. McClure, Conservation of ground-water of the Roswell Basin, Johnson National Drillers J., v. 8, No. 4, pp. 1-77, July-Aug., 1936.

[38] O. E. Meinzer, Review of the work of W. J. McGee on ground-water levels, Trans. Amer. Geophys. Union, pp. 386-390, 1936.

[39] O. E. Meinzer, R. C. Cady, R. M. Leggette, and V. C. Fishel, The channel-storage method of determining effluent seepage, Trans. Amer. Geophys. Union, pp. 415-418, 1936.

[40] O. E. Meinzer, Our water-supply, Wash. Acad. Sci., v. 27, No. 3, pp. 85-101, March 15, 1937. (Discusses the role played by water in physical processes, in life-processes, and in human activities. Traces the hydrologic cycle and discusses the emergence of hydrology as a recognized science.)

[41] O. E. Meinzer, Movement of ground-water, Amer. Assoc. Petroleum Geol. Bull., v. 20, No. 6, pp. 704-825, June, 1936.

[42] O. E. Meinzer, L. K. Wenzel, and others, Water-levels and artesian pressure in observation-wells in the United States in 1935, U. S. Geol. Sur. Water-Supply Paper 777, 268 pp., 1936.

[43] D. C. Muckel, Some factors affecting the rate of percolation on water-spreading areas, Trans. Amer. Geophys. Union, pp. 471-474, 1936.

[44] Morris Muskat and M. W. Meres, The flow of heterogeneous fluids through porous media, Physics, v. 7, No. 9, pp. 346-363, 1936.

[45] Morris Muskat, The seepage of water through porous media under the action of gravity, Trans. Amer. Geophys. Union, pp. 391-395, 1936.

[46] Sidney Paige, Effect of a sea-level canal on the ground-water level of Florida, Econ. Geol., v. 6, pp. 537-570, 1936.

[47] P. H. Price, J. B. McCue, and H. A. Hoskins, Springs of West Virginia, Proc. 10th Ann. Conf. Water Purification, W. Va. Coll. Eng. Tech. Bull., No. 8, pp. 90-125, 1936; abstract by C. B. Jenni in Chem. Abs., v. 30, No. 47, p. 7733, 1936.

[48] J. D. Restler, Water-supplies from underground sources, Swiveyer, v. 87, p. 283, 1935; U. S. Pub. Health Eng. Abstracts, 15, W. 147, Dec., 1935; abstract by C. R. Fellers in Chem. Abs., v. 30, No. 5, p. 1474, 1936. (The advantage of ground over surface-sources of water-supply are stressed.)

[49] T. W. Robinson, Decline of artesian head in west-central South Dakota, Trans. Amer. Geophys. Union, pp. 363-366, 1936.

[50] A. N. Sayre, The relation of the drought of 1934 to ground-water supplies in the James and Sheyenne river-basins of North and South Dakota, Amer. Geophys. Union Trans., v. 2, pp. 366-371, 1936.

[51] A. N. Sayre, Geology and ground-water resources of Uvalde and Medina counties, Texas, U. S. Geol. Sur. Water-Supply Paper 678, 146 pp., 1936.

[52] C. M. Saville, The underground water-index: Its relation to surface-runoff, Trans. Amer. Geophys. Union, pp. 382-386, 1936. (This paper is based on a study that was made to obtain a correlation between ground-water levels, ground-water runoff, surface-runoff, and precipitation.)

[53] L. K. Sherman, The Horton method for determination of infiltration-rates, Amer. Geophys. Union Trans., pp. 312-314, 1936.

[54] Bayard F. Snow, Tracing loss of ground-water, Eng. News-Rec., v. 117, No. 1, pp. 1-6, July 2, 1936. (A study of lowering of ground-water Level in the vicinity of the Public Library and Trinity Church in Boston, Mass. With damage to piling under buildings, several hundred wells driven for observation as part of a Works Project Administration project.)

[55] A. L. Sonderegger, Remarks on water-spreading, Trans. Amer. Geophys. Union, pp. 474-476, 1936.

[56] H. T. Stearns, Origin of the large springs and their alcoves along the Snake River in southern Idaho, J. Geol., v. 44, No. 4, pp. 429-450, May-June, 1936.

[57] H. T. Stearns, Lynn Crandall, and W. G. Steward, Records of wells on the Snake River Plain in southeastern Idaho, U. S. Geol. Sur. Water-Supply Paper 775, 139 pp., 1936.

[58] Gilbert I. Stewart, The use of shallow wells in forest-fire suppression, Michigan Dept. Conservation, pp. 1-64, 1934.

[59] C. G. Stipe and S. F. Kelly, Geophysical methods aid construction work, Civil Eng., v. 7, No. 4, pp. 264-268, April, 1937.

[60] E. E. Stohsnet, Santa Clara Valley subsidence has now reached 5 feet, Eng. News-Rec., v. 118, pp. 479-480, April 1, 1937.

[61] V. T. Stringfield, Artesian water in the Florida Peninsula, U. S. Geol. Sur. Water-Supply Paper 773-C, 115-195.

[62] G. H. Taylor and R. M. Leggette, Ground-water relieves drought emergency, Eng. News-Rec., v. 115, No. 11, pp. 359-361, Sept. 12, 1935. (Summarizes development of water-supply for Salt Lake City, the geology and ground-water conditions of the Jordan River valley, and the development of 14 wells capable of yielding 29.7 m.g.d. to relieve a serious water shortage caused by the 1934 drought. Discusses possible effect of new ground-water development.)

[63] G. H. Taylor, Fluctuations of ground-water levels in Utah, Trans. Amer. Geophys. Union, pp. 378-382, 1936.

[64] G. H. Taylor and H. E. Thomas, Ground-water investigations in Utah to June 30, 1936, by the United States Geological Survey in cooperation with the Utah State Engineer, in twentieth biennial report of the State engineer to the Governor of Utah for the biennium July 1, 1934, to June, 1936, pp. 91-106, 1936.

[65] C. V. Theis, Ground-water in south-central Tennessee, U. S. Geol. Sur. Water-Supply Paper 677, 177 pp., 1936.

[66] D. G. Thompson, Some problems relating to fluctuation of ground-water levels, Trans. Amer. Geophys. Union, pp. 337-341, 1936.

[67] D. G. Thompson and R. M. Leggette, Withdrawal of ground-water on Long Island, New York, New York State Department Conservation, Water Power and Control Commission Bull. G-W-1, 28 pp., 1936.

[68] F. H. Tibbetts, Water-conservation project in Santa Clara County, Trans. Amer. Geophys. Union, pp. 458-465, 1936.

[69] H. C. Troxell, The diurnal fluctuation in the ground-water and flow of the Santa Ana River and its meaning, Trans. Amer. Geophys. Union, pp. 496-504, 1936.

[70] Water Resources Committee, A preliminary report on water-conservation and utilization, North Dakota State Planning Board, 131 pp., April 10, 1936.

[71] L. K. Wenzel, The Thiem method for determining permeability of water-bearing materials and its application to the determination of specific yield, U. S. Geol. Sur. Water-Supply Paper 679-A, pp. 1-57, 1936.

[72] L. K. Wenzel, The recovery of ground-water levels in Nebraska in 1935, Trans. Amer. Geophys. Union, pp. 370-371, 1936.

[73] L. K. Wenzel, Several methods of studying fluctuations of ground-water levels, Trans. Amer. Amer. Geophys. Union, pp. 400-405, 1936.

[74] Wisconsin State Well Drilling Sanitary Code, Johnson Nat. Drillers' J., v. 8, No. 3, pp. 14-23, May-June, 1936; also the Driller, v. 10, No. 7, July 1936.

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REPORT OF COMMITTEE ON DYNAMICS OF STREAMS, 1936-37

Lorenz G. Straub, Chairman

It may be well at this time to review briefly the field of study of the Committee on Dynamics of Streams. The Committee is concerned with the flow of water in rivers and smaller streams, the forces which the water exerts, the work which it does in erosion, transportation and deposition, and the relation between the streams and the channels they occupy. It is also concerned with the dynamics of rain- and surface-waters in soil-erosion.

Research in the field, laboratory, and by means of analytical mechanics is being pursued and fostered by the Committee in order that the investigations might be as comprehensive as possible. The Committee is interested in the accumulation of scientific data as such, but also with a view to the utilization of these data in practical problems. Thus, an attempt to define the natural laws governing the transportation of sediment by streams is a specific aim, but the formulation of this new information so that it may be used in the design of river regulation-works is likewise an important consideration.

By action of the Executive Committee of the Section of Hydrology during the past year the Committee on Dynamics of Streams was assigned an additional field of study which is closely related to its present activities, namely, the study of "land forms," as related to the hydrology, geology, and dynamics of streams.

A number of papers on stream-dynamics have been contributed by members of the Committee. These contributions are referred to individually in the literature forming a part of this report.

There are a few changes in the personnel of the Committee. The present membership follows this report.

Organizations active in fields related to dynamics of streams--There are at present several committees actively engaged in studying problems related to the dynamics of streams. Thus, the Special Committee on Hydraulic Research of the American Society of Civil Engineers [see I of references at end of report], of which J. C. Stevens is chairman, is sponsoring several laboratory research-projects. It is also preparing a Manual on Hydraulic Laboratory Practice which is intended particularly to deal with the applications of the principles of similitude as related to many types of problems of river-hydraulics. The research-projects of the Committee of the American Society of Civil Engineers, which are supported in part by funds from the Engineering Foundation, include the following: "Traveling waves on steep slopes," by Harold Thomas, Carnegie Institute of Technology; "Curves in open channels," by C. A. Mockmore, Oregon State College; "Phenomena of intersecting streams," by M. P. O'Brien, University of California; "The conversion of kinetic to potential energy," by F. T. Mavis; and "Sedimentation at the confluence of rivers," by L. G. Straub, University of Minnesota.

A subcommittee on hydrodynamics has been formed under the National Research Council [2] under the chairmanship of W. W. Rubey, which has as its purpose the "application of hydrodynamics to problems of geology."

The Institution of Civil Engineers has set up a subcommittee on velocity formulas for open channels and pipes, under the chairmanship of W. J. Binney, which includes under its purpose the collection of information relative to flow in channels, including the effect of silt in suspension, the evolving of basic formulas, and the suggestion of needed research where necessary [3].

In addition to the foregoing there are outside of the Geophysical Union research committees a number of other committees whose work more or less overlaps that of the Committee on Dynamics of Streams. Among these are: Committee on Flood-Protection on Data, Committee on Flood-Control, and Committee on Seepage and Erosion of the American Society of Civil Engineers; Committee on Symbols and Abbreviations of the American Standards Association; the Hydraulics and Applied Mechanics Section of the American Society of Mechanical Engineers; International Association for Hydraulic Structures Research; and Committee on Applied Hydraulics of the Society for the Promotion of Engineering Education.

Laboratory-research--The investigation of many types of streams dynamics problems has been constantly on the increase in laboratories throughout the country. Unquestionably part of this acceleration of activity in experimental work has been brought about by exchange of information on hydraulic research fostered by the Hydraulic Laboratory Section of the National Bureau of Standards on "Current hydraulic laboratory research in the United States." Several of the laboratories have as their primary purpose the experimental solution of river problems with a direct application to immediate construction measures. This is particularly true of most of the work under the supervision of the United States Engineer Corps [4]. The results have been so gratifying that at present hardly any complex and important river hydraulic projects are executed without first subjecting the design to laboratory experimental analysis. In many instances experiments have been made out of doors in order to obtain sufficient unobstructed space for the models. Many of the Mississippi River models have been constructed out of doors, for the most part at the United States Waterways Experiment Station at Vicksburg, Mississippi [4]; also models of the Columbia River projects, most of which have been constructed out of doors near Portland, Oregon; and models for some of the projects of the United States Bureau of Reclamation [5].

Some of the laboratories concerned with the river hydraulic phenomena have come to serve a dual role, namely, the experimental study of designs for projected river improvements, and the scientific study of stream dynamics occurrences.

At the Hydraulic Laboratory of the National Bureau of Standards studies are being made to determine the laws governing "Currents in lakes and reservoirs." An attempt is being made to determine the cause of the occasional occurrences of currents of silty waters in reservoirs, such as have been observed at the Elephant Butte Dam and the Boulder Dam. Investigations are also being made here of various flow phenomena in open channels; other studies at this Laboratory include experiments by the Soil-Conservation Service on various types of measuring flumes, silt-sampling apparatus, etc. Investigation of artificial controls for stream-flow measurements by the United States Geological Survey.

Studies of bed-load movement are being made at a number of laboratories, including the United States Waterways Experiment Station at Vicksburg, the National Hydraulic Laboratory at Washington, D. C., the laboratory of the United States Engineers at Portland, Bureau of Reclamation, universities of California, Iowa, and Minnesota, and Massachusetts Institute of Technology.

Varied flow conditions in open channels including the hydraulic jump on horizontal and sloping channels, friction factors, wave phenomena, and the like are being investigated at the California Institute of Technology, Carnegie Institute of Technology, Columbia University, Cornell University, University of California, University of Iowa, Massachusetts Institute of Technology, Minnesota, Washington State College, the Horton Hydrologic Laboratory, and others, as well as at a number of laboratories of the United States Government.

Expansion of facilities of a number of the laboratories has taken place in the course of the last year or two. The Tennessee Valley Authority has developed its facilities; New York University has established a new laboratory; California has added a tidal basin; the University of Washington has added facilities; the University of Minnesota is constructing a large-scale laboratory on the Mississippi River at the head of St. Anthony Falls, which is to be used primarily for stream dynamic studies [6]. The laboratories of several other universities, as well as a number of governmental laboratories, have been considerably expanded.

Review of literature on dynamics of streams

During the past two years a wide variety of publications has appeared regarding problems in the field of dynamics of streams. There has been a definite tendency toward closer correlation of theoretical considerations with observations in field and laboratory.

Uniform and varied-flow phenomena, flood-waves, hydraulic jump--The movement of flood-waves in natural and artificial channels has recently received more than usual attention. Studies have been made of the application of the theory of probability to high-water waves [7], and methods of computation and prediction of high-water conditions in rivers [8, 9]; other studies concern varied discharge-conditions, particularly as related to flood-waves [10, 11], giving information regarding the flattening of such waves and analytical treatment of flood-waves in a channel with quadratic frictional resistance introducing "shape-factor" [12]. Other studies concern the velocity of propagation of flood-waves in open channels [13, 14, 15], some with especial reference to low waves [16], cross-sectional variations of the channel and frictional influences [17], critical values of the speed of generation of artificially produced waves at which progressive waves disappear, giving way to undulating stationary waves [18], and the significance of swells in determining the shore-elevation of headrace canals [19]. Experiments have been made to determine the wave-resistance of completely submerged bodies with a view of determining the possibility of practical use of mathematical methods of analysis [20, 21]. Attempts have been made to set up conditions which must be fulfilled in order that a wave progressing through a canal continually develops a steeper wave-front which eventually breaks (instead of flattening) [22]; investigations have been made regarding the transmissibility of long waves along a canal with abrupt changes in depth, indicating partially reflected waves at points of abrupt rise and lowering of the bottom of canal [23]. At the XVIth International Navigation Congress at Brussels in September, 1935, a number of reports were presented regarding wave-motion phenomena [24]; some of these reports refer particularly to problems pertaining to experiments in field and laboratory, theoretical analyses of wave-motion phenomena and an attempt to correlate experimental results with theoretically computed values.

Importance of giving special consideration to channels having steep slopes is becoming generally recognized [25, 26]; it has been shown theoretically and verified by experiment that in the case of rectilinear flow in steep channels the pressure-head within the fluid is not equal to the vertical distance from the water-surface, but substantially less. Traveling waves in steep channels have also been investigated [27].

The hydraulic jump and various phenomena related thereto has been studied [28], particular attention having been given to the length of the jump surface-roller [29, 30] and relatively low jumps where no surface-roller occurs [31]. An analysis has been made of the transition from shooting to streaming flow in a channel of semicircular cross-section [32], also studies of the design of canal-transitions [33, 34, 35]. Mixing occurrences for the case of abrupt cross-sectional changes have been discussed with application to particular examples such as the hydraulic jump, weir, overfalls, and so forth [36]; an approach has been made to the computation of energy-losses in the connecting stretch between a broad off-take and an inclined canal [37]. Analyses have been published concerning the theory of flow in channels curved in a vertical plane [38, 39], also concerning flow-forms in a channel of small exponential divergence [40].

A number of contributions have been made concerning back-water and drop-down curves for the case of constant discharge-conditions [41, 42, 43, 44], including studies based upon the Belanger differential equation [45], and investigations in the case of channels of adverse slope [46].

Discharge-formulas, channel-roughness, discharge-measurements, velocity-distribution--Although considerable progress has been made in the analysis of various open-channel flow-phenomena, the precise measurement of rates of flow and the interpretation and formulation of various kinds of channel-roughness have not advanced particularly rapidly. It has been pointed out that the Venturi type of device provides an especially good means of measuring discharges in open channels [47, 48, 49] under some circumstances. Observations have been made on the use of current-meters for accurate flow-measurements [50, 51] including the effect of inertia of the instrument, oblique direction of flow toward the meter, and turbulent-flow conditions [52], with the conclusion that two to five per cent error may be expected in discharge-observations [53]. Recent investigations have been made of the Gibson method of measuring flow [54, 55], of optical methods [56, 57], of the salt-velocity method [58], and of other procedures [59, 60]. Observations on Pitot tubes [61] indicated that over a wide range the coefficient is practically independent of Reynolds' number, and that up to a 6°-inclination of the tube-opening relative to the direction of flow, the cosine-value of the velocity was indicated; the effect of vibrations of the tube or velocity-pulsations upon the readings were also investigated [62]. New velocity-measuring devices have been invented: the Bentzel velocity-tube [63], which operates somewhat similar to a Pitot tube but is particularly useful for lower velocities, and the spherical pitometer [64] are noteworthy.

Some discussion has been given to the various discharge-formulas for open channels [65, 66, 67, 68] and new ones have been proposed [69] for artificial channels, also for flow of water in thin sheets [70]. Various nomographic charts have been developed for discharge-formulas [71, 72]. Flow-observations were made on the irrigation-canals in the Po District and used to determine roughness-coefficients [73]. A number of other studies of roughness- and friction-factors have been made recently [74, 75, 76, 77]. Artificial roughness in open channels has been compared with the classical experiments of Nikuradse with pipes where roughness was produced by sand-grains over the walls of the pipe [78]. Some discussion has been given to the suitability of taking the hydraulic radius for various types of stream cross-sections in connection with discharge-determinations [79, 80, 81, 82].

The question of velocity-distribution in open channels has been a mooted one during the past two years. Conclusions have been drawn that a quarter ellipse represents the velocity-distribution value in natural wide rivers [83]. Another investigation shows the distribution of average velocities in uniform turbulent-flow to be dependent upon the shape of the channel cross-section and upon the relative change of cross-section along the wetted perimeter [84,85]. Other studies concern the determination of the water-discharge of a river from the cross-section and surface-velocities [86,87], the location of the water-surface taking into account the velocity-distribution [88], natural stream-channel storage, and critical depth in trapezoidal channels [89, 90].

Sediment-transportation by rivers, suspended load, bed-load, sedimentation, river regimen, soil-erosion--Studies in the various fields related to the movement of sediments by flowing water have been made with highly accelerated interest during the past several years. Although there is no clear-cut division between various related occurrences, the phenomena may be generally grouped into erosion, sedimentation, suspended-load transportation, and bed-load transportation.

In recent years observations of suspended load have been made on many rivers [91, 92, 93, 94, 95, 96], also in connection with experiments on models [97]. Observations have also been made of the dissolved mineral-matter in rivers [98]. Interesting observations are reported of the flow of a silt-laden stream through a clear-water reservoir [99]. Theories of turbulence have been proposed to define the suspended-load distribution in rivers [100, 101]; observations have been reported on the transportation of sediment in suspension [102], also general discussions have been published of stream-transportation of solids [103, 104, 105].

A number of surveys have been made of the rate of silting of reservoirs [106, 107, 108] and analyses of designs that have been proposed for various types of desilting-works [109, 110, 111, 112, 113, 114, 115]. A theory of probability applied to analysis of sedimentation of silt in turbulent streams has been presented; the theory is based upon experimental investigations [116]. Studies have been made of the velocity of deposition of river-sediments [117] and dust-particles [118], sedimentation in basins [119], and the settlement of suspended material in water flowing through a long tube [120]. Observations were made of the velocity of fall of smooth spheres, discs, and prisms in water and compared with the rate of fall of irregular bodies of coal, sandstone, and other minerals [121]. Other idealized experimental studies concern tests undertaken for determining the influence which spherical and cylindrical bodies have on one another when placed in a stream of air [122].

Since the time of the establishment of the Federal Soil-Conservation Service a few years ago, research in this field has developed rapidly. It has become generally recognized that in many parts of the United States rich agricultural lands are rapidly becoming barren because of the effects of erosion of the top soil [123, 124]. Considerable discussion has been given to methods of controlling erosion [125, 126, 127]; observations have been made to determine relationships between slope-length, surface-runoff, and the silt-load [128].

Many studies in the laboratory and observations in the field have been made of bed-load transportation of rivers in this country as well as abroad. Observations in the National Hydraulic Laboratory indicate that scour of a sandy river-bed is greater by clear water than by muddy water, other conditions being equal [129]. A number of efforts have been made to arrive at a relation between the bed-load for normal breadth and slope of rivers [130, 285, 131], also to determine the relations between the values of Chezy's coefficient, C, and the roughness-coefficient, n, on the one hand, and the size and other peculiarities of the bed-load on the other [132]. The applicability of model-experiments in which bed-load transportation takes place has received attention [133, 134, 135, 136, 137], particularly where migrating bars are not evident [138]. The theory of probability has been introduced in the analysis of bed-load transportation [139]; the kinematics of detritus-movement has also been treated [140]. The circulation-theory has been applied to detritus-transportation [141]. The pulsations in detritus-movement are discussed with an explanation based upon laws of potential-flow. Observations are recorded of the transportation of coarse materials in flumes under idealized conditions and results have been formulated [142, 143, 144]. Other studies concern the design of non-silting channels in erodible materials [145, 146], the formation of bars [147], the variation in depth of a river-bed in consequence of variation of water-discharge cycles [148], the sorting of river-sediments [149], and various other presentations regarding the regimen of rivers [150, 151, 152, 153, 154].

Turbulence, viscosity, surface-tension, obstructions--The importance of the internal mechanics of flow is rapidly becoming recognized in the analysis of many stream-dynamics problems. Various aspects of turbulence have become mooted subjects in the past few years. It has been suggested that the laws of transportation of suspended load and detritus have not been investigated [155]; transverse-currents and velocities of progression in the immediate vicinity of the bed play an important role. Discussions have been given relative to the vertical distribution of eddy-viscosity in rivers [156], also concerning turbulent boundary-layers with pressure-gradients in the direction of flow [157]. Several papers have been presented giving general and individual aspects of the turbulence-problem [158-183]. Discussions have been presented concerning measurement of viscosity and the physical properties of water [184, 185, 186], also relative to measurement of surface-tension by means of stationary waves on the vertical jet [187], and the surface-tension of a moving water-sheet [188]. Experimental investigations have been made of the viscosity-effects in a channel of small exponential divergence [189]; also studies of the energy-dissipation in the case of abrupt enlargement of cross-section [190]. A number of discussions relate to obstructions of channels [191, 192], particularly with reference to bridge-piers in river-channels [193, 194, 195, 196].

River-regulation, shore-protection works, cut-offs, scour, models--The development of various types of river-regulation works and the improvement of rivers for flood-control, navigation, and power-development in this country has been at a peak for the past several years; work has also been progressing steadily abroad [197]. Several descriptions have appeared on the regulation of foreign rivers, particularly in continental Europe [198, 199, 200, 201, 202, 203, 204, 205]; general descriptions of regulation-works in America during the past two years concern more particularly the Mississippi River System [206, 207, 208, 209, 210, 211], although extensive studies have been made of the entire water-resources of the country [212, 213]. Extensive work has been under way to straighten and shorten the Lower Mississippi by means of cut-offs [214, 215], a construction measure which is still under way on some of the European rivers [216]. A number of types of shore-protection works are being developed including concrete tetrahedrons [217], articulated concrete-block revetment [218, 219], asphalt-mattresses [220, 221], wire-bound rock-walls [222, 223], and other types [224, 225, 226]. Check-dams for torrential streams have been given some discussion [227, 228, 229]; also sills in the case of larger streams [230]. Publications have appeared regarding the effect of partial regulation of a water-course upon the flood-flow [231]; and the influence of lengthening of a stream in contrast to shortening by means of cut-offs [232]. The combating of scour below dams and weirs remains a field of investigation for individual projects [233, 234, 235, 236], in many of which models have been used. The limitations of principles of similarity for various types of river-models has been discussed from various view-points [237, 238, 239, 240, 241, 242, 243, 244, 245].

River-estuaries, sea-coasts, seiches, tides--Many geophysical problems in the field of dynamics of streams are more particularly influenced by tides and atmospheric disturbances. Some attention has been given to the study of tidal effects on river-mouths by means of models [246, 247], with consideration of the questions of ynamical similarity, distortion of scale of models, and the choice of bed-materials [248]. On the basis of model experimental work recommendations have been made as to the procedure for dredging to obtain sufficient navigable depth [249]. Analytical methods have been presented for computing tidal influences for estuaries [250, 251, 252, 253, 254, 255, 256, 257], also for determining conditions of sedimentation [257, 258]. A number of other treatments regarding tides and flood-waves deal with the effect of the surges upon various kinds of wave-breakers [259, 260, 261, 262, 263] and shore-protection works [264, 265, 266, 267, 268, 269]. A number of publications treat the theory of seiches produced by wind and barometric gradient [270, 271], tides in a channel [272, 273], the seiches in an epicontinental sea [274], seiches in lakes [275, 276], oscillations on a continental shelf [277], and other wave and oscillatory occurences [278, 279, 280, 281, 282, 283, 284].

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University of Minnesota,
Minneapolis, Minnesota

REPORT OF THE COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1936-37

C. S. Howard, Chairman

The membership of this Committee is as follows:

C. S. Howard, Chairman, U. S. Geological Survey, Washington, D. C.
D. G. Thompson, U. S. Geological Survey, Washington, D. C.
A. C. Lane, 22 Arlington Street, Cambridge, Massachusetts
C. S. Scofield, Bureau of Plant Industry, U. S. Dept. Agri., Washington, D. C.
I. A. Denison, U. S. Bureau of Standards, Washington, D. C.
T. G. Thompson, University of Washington, Seattle, Washington
W. P. Kelley, Citrus Experiment Station, Riverside, California

In order to provide for close cooperation between the work of the different research-committees of the American Geophysical Union it was decided to have the chairmen of certain committees serve on other committees. The Chairman of the Committee on the Chemistry of Natural Waters is serving on the Committee of Underground Waters and D. G. Thompson as Chairman of the Committee on Underground Waters is serving on the Committee on Chemistry of Natural Waters.

The results of studies on the corrosion of metals in soils described in previous reports of this committee are given more fully in a recent report by Dr. I. A. Denison entitled, "Electrolytic measurement of the corrosiveness of soils." This report was published as Research Paper 918 of the National Bureau of Standards as part of the Journal of Research of the National Bureau of Standards (v. 17, September, 1936). An abstract of this paper is as follows:

"The electrolytic behavior of steel in contact with 47 soils of known corrosiveness was studied by means of a cell in which both electrodes were steel and the electrolyte was moist soil. By providing differential aeration of the electrodes the cell was enabled to develop its own electromotive force. Measurements were made of the voltage, current, and resistance of such cells. The relation between the current-density and applied voltage was also studied. The losses in weight of the test-specimens were related to the average current-density over a certain range of applied voltage and to the total quantity of electricity produced in the corrosion-process. The corrosion of the specimens in the laboratory-tests was correlated with corrosion experienced in long-time field-tests. The results of the tests may be applied practically in predicting the corrosiveness of soils toward iron and steel. However, they cannot be applied to the prediction of leaks or to the estimation of the useful life of a section of pipe-line until the relations connecting depth of pitting with exposed area and time can be established."

Dr. Denison reports that more detailed studies show that certain ions which in high concentrations are extremely corrosive to steel are actually protective to lead.

The work of sealing abandoned coal-mines in Pennsylvania and in West Virginia and the subsequent decrease in the acidity of drainage-waters from these mines was described at a meeting of the American Institute of Mining and Metallurgical Engineers in New York in February, 1937.

During 1936 the water-resources of the Rio Grande Valley were studied in the Rio Grande Joint Investigation of the National Resources Committee. In connection with the study of the chemistry of the natural waters of the Basin samples were collected from the main stream near the source and near the head of Elephant Butte Reservoir and from tributary streams and also from wells in the Basin. Conductance-determinations were made on over 5000 samples collected periodically from surface and underground waters. Complete analyses were made of nearly 500 samples collected during the year. This analytical data together with the other available analytical data for the Rio Grande Valley was compiled by C. S. Scofield. The compilation and a discussion interpreting the data were submitted by Mr. Scofield to the National Resources Committee.

For the last three or four years studies have been made at the University of Florida to determine the quantity of fluoride in the public water-supplies of the State of Florida. Prof. A. P. Black has supervised the work which was carried on with the cooperation of Herman Gunter, the State Geologist, and the State Board of Health. Professor Black has furnished the following abstract of this work:

"We have just tabulated the results of the analysis of 498 samples taken from an area comprising about 2/3 of the State. We hope to complete the survey of the entire State within the next six months. Of these 498 samples, 21 per cent contained less than 0.1 ppm of fluorine; 31 per cent contained from 0.1 to 0.5 ppm; 13 per cent contained from 0.5 to 1.0 ppm; and 169 samples, or 35 per cent contained from 1.0 to 3.7 ppm of fluorine. This is not as bad as it might seem, however, for the great majority of the waters high in fluorine were derived from a relatively small area in southwest Florida included in Manatee, Hardee, Sarasota, DeSoto, Charlotte, Glades, Lee, and Hendry counties.

"Mr. Gunter made a study of the results of our first survey in 1934 and his tentative conclusion was that all, or practically all of the waters "high" in fluorine were derived from a single geological formation, the Hawthorne, It is a phosphatic marl and is widely developed as a source of water supply in southwestern Florida."

Professor Black, as chairman of a special committee of the American Water Works Association, has arranged for a study of the available methods for the determination of fluorides in water for the purpose of comparing the results obtained by different analytical methods.

U. S. Geological Survey,
    Washington, D. C.

REPORT OF THE COMMITTEE ON RAINFALL, 1936-37

Merrill Bernard, Chairman

On October 2, 1936, announcement was made that the Executive Board had discontinued the Committee on Rainfall and Runoff and had created separate committees on runoff and on rainfall. Upon conferring with W. G. Hoyt, the newly selected Chairman of the Committee on Runoff, the members of the retiring Rainfall and Runoff Committee were distributed between the two newly formed committees. Those accepting membership on the Rainfall Committee are:

- W. W. Horner
- W. G. Hoyt
- J. B. Kincer
- Carroll Merriam
- Thorndike Saville
- Charles W. Sherman
- L. K. Sherman
- Mary O. Soroka
- C. W. Thornthwaite
- H. C. Willett
- D. L. Yarnell
- Robert E. Horton
- C. H. Eiffert
- David E. Donley
- Merrill Bernard, Chairman

The only activity of the Committee undertaken in the current year has been the preparation of abstracts of American work on rainfall published in the period May, 1936, to April, 1937, which shall become the contribution of this Committee to the international bibliography.

The Committee has approved a project sponsored by the Water Resources Committee of the National Resources Board, the objective of which was to inventory sources of unpublished hydrologic data.

Particularly to be noted is the research-program of the Soil Conservation Service in which rainfall as a principal factor in the hydrolotic cycle has a prominent place. On the two experimental watersheds established by the Section of Watershed Studies rainfall-rate, duration, and distribution will be studied in detail.

Two noteworthy projects embracing rainfall-studies were inaugurated during the year. The first, by Dr. C. W. Thornthwaite of the Soil Conservation Service, has established 500 recording rain-gages on the Muskingum Watershed in Ohio. The project has as its purpose research on storm morphology. The second is a project to be undertaken cooperatively between the United States Weather Bureau, the United States Geological Survey, and the State of Pennsylvania. While the objective of the project is the development of forecasting-methods for the Weather Bureau, it is expected that it will also become a valuable rainfall-study. Under the project it is planned to establish approximately 130 recording rain-gages on the Allegheny, Monongahela, Susquehanna, and Delaware river-basins.

The Committee has sponsored three papers on rainfall to be presented at the 1937 meeting of the Union on April 29 and 30 in Washington.

The Committee suffered the loss of two active members in the untimely deaths of Montrose W. Hayes, Chief of the River and Flood Division of the United States Weather Bureau, who died on November 16, 1936, and of David L. Yarnell, Senior Engineer of the Bureau of Agricultural Engineering, who died on March 9, 1937. Mr. Hayes was an active member of the Rainfall and Runoff Committee. He was deeply interested in the science of hydrology and made contributions to its advancement. Mr. Yarnell was an outstanding student of hydrology and made valuable contributions to the subject, the most important of which is perhaps his work "Rainfall intensity-frequency data published by the Department of Agriculture.

U. S. Weather Bureau,
Washington, D. C.

PAPERS

PRELIMINARY REPORT ON A DETERMINATION OF COMPARATIVE INFILTRATION-RATES ON SOME MAJOR SOIL-TYPES

G. W. Musgrave and G. R. Free

Infiltration-rates for different soil-types undoubtedly vary by wide margins. It is also evident that any given soil-type may have a rather wide range of infiltration-rate under different conditions. Many factors influence the rate in rather large degrees [see 1 of references at end of paper] including:

(a) Soil-structure (total amount and average size of pore-space occurring naturally or, as modified for example by tillage or the incorporation of coarse organic matter).
(b) Soil-moisture (as in the case of the presence of considerable amounts of colloids which swell in the presence of water, or in the filling of pore-space by water).
(c) Turbidity of the water which is applied to the profile.

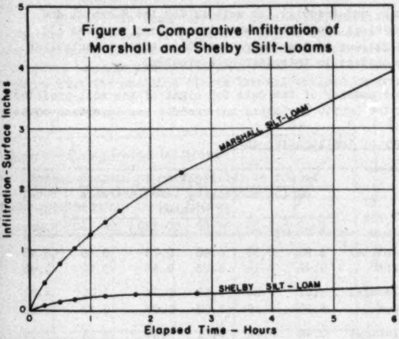
Figure 1 – Comparative Infiltration of Marshall and Shelby Silt-Loams

Other factors which affect the infiltration-rate but whose effects usually are of lesser magnitude are:

(a) The degree and kind of cation saturation.
(b) Temperature in its effects upon the viscosity of water. (There is also the case, of course, where frozen-ground conditions either completely inhibit infiltration or, if dry at time of freezing, greatly increase the rate. High-intensity rains occur upon frozen-ground conditions only at rare intervals, and the frequency of occurrence of this effect is not great, although upon occasion it is of large magnitude.)

Thus, specific values for the infiltration-rate of a soil-type are virtually non-existent and measured rates are of value largely from a comparative and relative viewpoint. With the very large number of major soil-types in this country presenting a problem which is difficult of solution by means of the accumulation of records of runoff and the preparation of hydrographs, other methods for ascertaining relative differences between soils have been sought. Even were it possible to accumulate records of runoff from these soils, relative infiltration-rates would frequently be masked by such factors as degree of slope, length of slope, vegetative cover, tillage-operations, variations in soil-moisture, and temperature.

This paper is merely a preliminary report citing results of work still in progress in which the tube-method of ascertaining an index of relative infiltration has been used on some of the major soil-types in the Southeast Coastal Plain and Piedmont Region. That this method has some value in forecasting relative runoff from different soils has been previously shown [2].

Figure 1 shows the relative infiltration for the Marshall and Shelby silt-loams where the artificial application of clear water by means of the tube-method is used. In these two soils measured runoff has been recorded at the Clarinda, Iowa, and Bethany, Missouri, erosion-stations, where, for the period of comparison, the ratio of water-loss Shelby to Marshall has been in one series of plots 6.8:1 and in another series 7.2:1. Since the rains producing these losses have averaged a duration of slightly less than one hour, there is reasonably good agreement between the measured relative infiltration and that indicated by the runoff-method. Accordingly, this previously reported method has been applied to soils in situ.

The selection of the southeast area for these determinations was based upon both the need and the opportunity for initiating work in this region during recent months. The soil-profiles upon which measurements were made were selected in consultation with local soil-specialists to meet the following desiderata: (a) Representativeness of the chosen soil-type; (b) similarity of treatment or culture of the profiles during the past two years; (c) accessibility of the profiles to the headquarters of a field-party.

In addition to selecting soil-profiles typical of the major soil-type in certain instances, profiles were selected which ranged by gradation from a near virgin condition (little erosion) to a severely eroded condition.

Methods

Tests with clear water--In all instances measurements were made with 20 to 24 replications for each determination, the first determination being a 3-hour continued application of clear water upon soil of field moisture-content and the second a similar application upon the same units 24 hours later for the purpose of providing data upon the thoroughly wet profile.

At each site soil-samples were taken and sent to the laboratory to provide data upon: (a) Actual soil moisture-content; (b) real and apparent specific gravity (to determine porosity); (c) mechanical and aggregate analysis; (d) organic-matter content; (e) moisture-equivalent; and (f) other chemical and physical properties as may later be desired.

Upon three of the soils (Cecil, Davidson, and Iredell), as well as for the Marshall and Shelby previously cited, the chemical and physical properties have already been reported [3]. From these and additional supporting investigations in the laboratory it is hoped to establish at least some of the cause-and-effect relationships in this intricate problem.

Results from clear-water tests--A simple summary of the data for eight of the soil-profiles is presented in Table 1. Of these profiles the Cecil, Davidson, and Iredell are important soils of the southern Piedmont, while the Ruston, Greenville, and Susquehanna are extensive types of the Coastal Plains. The three profiles of Cecil (Cecil sandy loam, Cecil sandy clay-loam, Cecil clay-loam) represent profiles having little erosion, considerable erosion, and excessive erosion, respectively. On these soils the amounts of infiltration occurring within three hours under the wet condition were 1.65 inches, 1.26 inches, and 0.28 inch, respectively. The data of the initial runs at field moisture-content remain to be correlated later with the soil-moisture determinations of these profiles; hence the present discussion is limited to the results of second or "wet runs" on each profile.

Table 1--Summary of infiltration-data

Soil	Depth of A-horizon, inches	Location of site in Georgia near	Kind of run	Amount of infiltration in surface-inches					
				During successive time-intervals in minutes					Total for 3 hours
				0-15	15-30	30-60	60-120	120-180	
Cecil sandy loam	11	Watkinsville	Initial[1]	1.21	0.33	0.45	0.78	0.69	3.45
			Wet[2]	0.42	0.14	0.23	0.43	0.42	1.65
Cecil sandy clay-loam	3	Watkinsville	Initial	1.01	0.28	0.48	0.78	0.75	3.31
			Wet	0.27	0.10	0.19	0.37	0.33	1.26
Cecil clay-loam	1	Watkinsville	Initial	0.42	0.04	0.11	0.15	0.14	0.86
			Wet	0.07	0.04	0.03	0.06	0.09	0.28
Davidson clay-loam	6	Monticello	Initial	1.22	0.62	1.20	2.18	2.06	7.28
			Wet	0.37	0.18	0.38	0.74	0.79	2.47
Iredell loam	6	Lexington	Initial	0.19	0.03	0.02	0.05	0.05	0.35
			Wet	0.01	0.00	0.01	0.00	0.01	0.04
Ruston sandy loam	8	Americus	Initial	2.33	1.21	2.26	4.39	4.22	14.41
			Wet	0.94	0.46	0.91	1.88	1.99	6.18
Greenville sandy clay-loam	3	Ellaville	Initial	0.88	0.11	0.11	0.22	0.21	1.53
			Wet	0.20	1.04	0.09	0.12	0.15	0.60
Susquehanna clay-loam	4	Ellaville	Initial	0.44	0.05	0.10	0.19	0.15	0.92
			Wet	0.04	0.03	0.05	0.07	0.10	0.29

[1] At field moisture-content.

[2] Same units as initial, repeated 24 hours later.

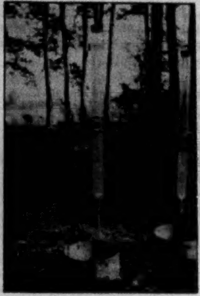

FIG. 2—INFILTRATION-TUBES, BURETTES, AND ACCESSORY EQUIPMENT, SOUTHERN PIEDMONT EXPERIMENT-STATION NEAR ATHENS, GEORGIA

The Davidson and Iredell are of particular interest in view of the fact that these are the same soils earlier studied by Middleton [4] who reported a much higher erosion ratio for the Iredell than for the Davidson.

It was shown that the texture of the Iredell and Davidson samples was nearly the same, that the total colloid-content was greater in the Davidson than the Iredell, but that the colloid of the Davidson does not remain in suspension, whereas that of the Iredell is highly dispersed. The ratio of colloid to moisture-equivalent of the samples studied was higher for the Davidson than for the Iredell. The ratio of the clay to silt-content likewise was higher in the Davidson than the Iredell. However, the slacking value was much greater in the Davidson, indicating a more permanent type of granulation of particles in this soil. This is of interest in view of the fact that the Iredell sample was nearly neutral in reaction, whereas the Davidson sample was acid. The pore-space of the Davidson was slightly greater than for the Iredell and the volume of voids increased through the profile, while it decreased through the profile of the Iredell.

Lutz [5], in studying these same soils, explains the erosive character of the Iredell as being due to the ease of dispersion and to the dense, impervious nature of the B-horizon. All of the Davidson colloids were flocculated, irrespective of the nature of the exchanged cation on the complex, whereas only the H-, Ba-, and Ca- saturated Iredell colloids were flocculated. He also shows that the swelling of the Iredell colloid is greater than that of the Davidson.

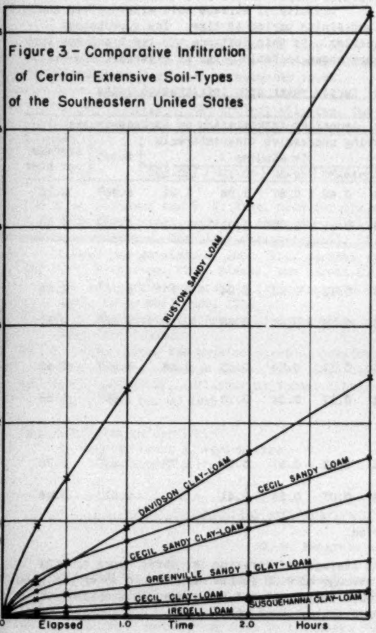

Figure 3 - Comparative Infiltration of Certain Extensive Soil-Types of the Southeastern United States

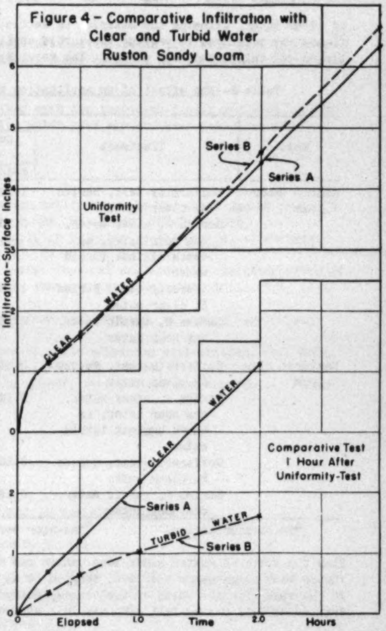

Figure 4 - Comparative Infiltration with Clear and Turbid Water Ruston Sandy Loam

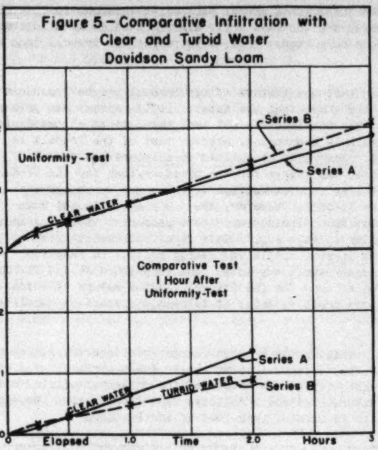

Figure 5 – Comparative Infiltration with Clear and Turbid Water Davidson Sandy Loam

In the data of Table 1 it is seen that the indicated total infiltration for a three-hour period was 2.47 inches for the Davidson and 0.04 inch for the Iredell.

The Ruston sandy loam, the Greenville sandy clay-loam, and the Susquehanna clay-loam gave a total infiltration for a three-hour period of 6.18 inches, 0.60 inch, and 0.29 inch, respectively. The curves of cumulative total infiltration are given in Figure 3.

A test with turbid water--Inasmuch as it has previously been shown [6] that infiltration commonly is greatly reduced where turbid water is applied, two of these soils were subjected to an application of turbid water, according to the following plan: For each soil-type, two sets of suitably replicated tubes were given a preliminary test for uniformity, using clear water only. One of these sets shows a slightly higher infiltration than its corresponding replicate. These units, giving a higher rate, received one hour later a corresponding treatment using turbid water. The turbid water was prepared by agitating a measured quantity of surface soil with a given quantity of clear water, allowing the material to settle a definite period of time. The supernatant liquid was then used to provide the turbid application. In this instance the treatment was continued for only a two-hour period. The results are shown in Table 2 and in Figures 4 and 5.

Table 2--The effect of an application of turbid water upon infiltration-rates

Soil	Treatment	Amount of infiltration in surface-inches						
		During successive time-intervals in minutes					Total	Average per hour
		0-15	15-30	30-60	60-120	120-180		
Ruston sandy loam	Uniformity-test, Series A, clear water	1.16	0.49	0.87	1.88	1.94	6.35[a]	2.12
	Series A, clear water, one hour later, as check against turbid water	0.70	0.51	1.00	1.91	....	4.12[b]	2.06
	Uniformity-test, Series B, clear water	1.16	0.43	0.95	2.04	2.13	6.71[a]	2.24
	Series B, turbid water, one hour later	0.36	0.30	0.40	0.58	....	1.64[b]	0.82
Davidson clay-loam	Uniformity-test, Series A, clear water	0.36	0.11	0.30	0.53	0.56	1.85[a]	0.62
	Series A, clear water, one hour later, as check against turbid water	0.12	0.17	0.34	0.70	....	1.33[b]	0.66
	Uniformity-test, Series B, clear water	0.32	0.13	0.31	0.60	0.72	2.09[a]	0.70
	Series B, turbid water, one hour later	0.19	0.07	0.24	0.41	....	0.91[b]	0.46

[a] Three-hour period. [b] Two-hour period.

Thus the units of Ruston sandy loam, which had an average infiltration for three hours of 2.24 inches when clear water was used, dropped to an average of 0.82 inches when turbid water was used. At the same time the units of the corresponding duplication which first showed an average infiltration of 2.12 inches fell off only to 2.06 inches in the check-run.

The same procedure was followed with two different sets of replicated tubes upon the Davidson clay-loam. The set which showed the highest infiltration during the uniformity-test--an average of 0.70 inch per hour, received the application of turbid water with a consequent reduction to 0.46 inch. The corresponding set which had an infiltration of 0.62 inch during the uniformity-test gave an average of 0.66 inch in the run with clear water one hour later.

There is thus a very evident difference in the infiltration-rate when turbid water is used, but the ranking of the two soils is the same whether clear or turbid water was used. Whether or not this would be true of all soils is not known. Presumably much would depend upon the degree of turbidity of the applied water and perhaps also the nature of the colloid which it contained. It is a point which requires further study and the extended plans of the project call for further investigation of it. At the present time, however, there is no reason to believe that the ranking of the eight soils shown in Table 1 would have been different had turbid water been used and in fact there is some assurance that a more comparable result has been secured through the use of clear water because of the consequent elimination of a variable turbidity-factor which at best would differ with the colloids of different soil-types.

Summary

The data indicating the relative infiltration for eight of the outstanding soil-profiles in the State of Georgia presented in this preliminary report indicate clearly that for a given intensity and duration of rainfall marked differences in runoff may be expected. It seems probable that treatments for the control of runoff must be much more rigorous upon the soils of low infiltration-rates, all other conditions being the same.

The data for three profiles of the Cecil series which have been previously subjected to various degrees of erosion differ widely and show the need of more extensive study of the factors which are involved.

Although several of these soils have such high infiltration-rates that one might question their susceptibility to erosion, the tests with turbid water indicate at least one of the reasons for the excessive erosion so commonly found.

A continuation of the project will deal further with the turbidity-factor and will include also further studies in the laboratory upon samples which have already been collected for the purpose.

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RAINFALL AND RELATIVE LOSSES IN VARIOUS FORMS

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Interest in rainfall and the consequent losses which occur from the land-surface in various forms has been manifested for many years by the membership of the Section of Hydrology as well as by other workers. During the past six years the Soil Conservation Service has been interested in this subject, recognizing that in the humid regions water is the primary agent of erosion and in the subhumid regions knowledge of the hydrologic cycle is important in connection with the conservation of water.

At various times many different workers have reported separately the results of their work on the measurement of precipitation, losses in the form of runoff, transpiration from various kinds of plants under various conditions, and evaporation of water either from soils or free water-surfaces. There has been very little work reported, however, in which these separate phases of the problem are studied in relation to each other. We have little information on the effect of the relative losses in one form upon the relative losses in some other form. It is desirable to know, for example, the effect of increased transpiration upon the relative movement of surface-water to ground-water, or the effect of reduced runoff upon consumptive use of water. It is desirable to know the relative effect, or at least the direction of trend of the effect of such factors as soil-type, degree of land-slope, length of land-slope, characteristics of rainfall, vegetal cover, temperature, soil-structure as affected by the chemical and physical properties of the soil and as affected by its mechanical treatment, and others of perhaps lesser importance upon the relative losses of precipitation from the land-surface.

In an attempt to arrive at a solution of some of these problems, studies have been under way since 1930. The work reported herein, however, is from a more elaborate later experiment dating from 1933. The results from this experiment are given as being indicative of possible general trends rather than as specific values, although they are reasonably precise for the conditions of the experiment.

Methods

The methods and equipment have been previously described by G. W. Musgrave (A device for measuring precipitation-waters lost from the soil as surface-runoff, percolation, evaporation, and transpiration, Soil Science, v. 40, No. 5, 1935, U.S. Dept. Agri. Bur. Chem. Soils). At this time it will suffice to state that they are based upon the use of tanks which contain soil of undisturbed structure from which free runoff and the movement of water below the 3-foot soil-column is permitted. Rather precise measurements of precipitation, runoff-losses, and loss of water below the root-zone of corn are regularly made, permitting the calculation of the vapor-loss (consumptive use) for several differing conditions. The comparisons include cropped and uncropped natural untreated Marshall silt-loam, and cropped and uncropped Marshall silt-loam into which there is incorporated annually in the surface six inches an application of coarse organic matter at the rate of 16 tons per acre. There is a further comparison of uncropped treated and untreated Marshall silt-loam with corresponding units of Shelby silt-loam, two types representing soils of high and low permeability, respectively. Each of the above conditions or treatments is in triplicate.

In 1932, Mr. Lee, Chairman of the Committee on Rainfall and Absorption, listed the requirements for dependable results from tanks as follows: (a) The quantity of soil should be great enough to permit normal development of the plant without interference with the processes of transpiration; (b) atmospheric conditions surrounding the tanks must be the same as those in the field; (c) plant-density must be the same in the tanks as in the field; (d) the soil in the tanks must be in the same physical condition as the soil in the field. To these requirements we would add another, namely, that free runoff must be permitted. It is obvious that in installations where free runoff is not permitted there is an enforced increase of absorption of meteoric water. There might be a further requirement indicated also. It is believed that the withdrawal of water from the base of the soil-profile should be in a manner to continue vertical downward movement, and not to enforce a lateral or horizontal movement through the soil-profile as it rests upon the floor of a pan.

As has been mentioned above, the experiment from which the data here reported have been obtained is the outgrowth of an installation similar to that first constructed by the senior author in 1930 at Temple, Texas. Some improvements in details of construction were incorporated in the experiment at Clarinda, Iowa, although the essential factors are the same and meet all of the requirements set forth. Similar installations subsequently have been made at the soil-erosion station at La Crosse, Wisconsin, and at Statesville, North Carolina. The University of Illinois at Urbana has likewise installed a battery of 24 units for the comparison of eight different soil-types.

The routine procedure connected with the operation of the experiment involves rainfall-determinations by means of the Friez recording rain-gage, two Weather Bureau type gages, and two specially constructed rain-gages which have the same exposure as the tanks themselves. One of the Weather Bureau type gages likewise is submerged to give an exposure above ground similar to that of the tanks.

Runoff is determined following each storm-period and calculated in the form of total water-losses and dry-soil losses; percolate is caught and measured in milliliters not less frequently than once each week. Particular precautions are taken to prevent evaporation from accumulated percolate during the interval between actual measurements.

Uncropped units are cultivated at the same time and to the same depth as cropped units, which normally is three times per season. Between periods of cultivation, weed-seedlings are removed by hand pulling. Cropped units have borders of plants similar to those within the experimental unit, similarly spaced in a manner to provide suitable buffers around the experimental units. On the units growing corn, the data for which are reported hereinafter, a pure-line strain of small-type corn is used in order to provide the greatest uniformity of plants, as well as to permit an adaptation of plant-size to the available amount of soil.

The experimental material as a whole, therefore, is extremely uniform and satisfactory. Particular precautions were taken in the first selection of the area, and later during actual construction there was opportunity to check rigorously against soil variability and to eliminate unsuitable profiles. Thus, the triplicate units with data covering four growing seasons provide massive and highly consistent material for analysis. The results have been subjected to various types of statistical tests and are found to be satisfactory to a high degree.

Results

Owing to limitations of space the results reported herein will be confined to simple totals and summaries of the various treatments. The detailed and individual data are being published in a more extensive report from the Clarinda Station.

Precipitation--The total precipitation for the first year (1933) of the experiment is slightly below normal (calendar year total 26.37 inches). For 1934 the total was only 23.62 inches; for 1935, slightly above normal, or 33.66 inches; and for 1936, 21.61 inches. There are thus represented by the data of the experiment two years of practically normal precipitation and two years of drought. In considering the results of the experiment for the period it is necessary to recognize that the effect of the drought-year (1934) may have been carried over into 1935 and may be reflected in the results of that year.

Runoff--In Table 1 are given the seasonal and annual runoff-losses from cropped and uncropped, treated and untreated Marshall silt-loam. Recalling that the untreated units consist of the normal Marshall profile, cultivated approximately three times each season, and that the treated units comprise those in which there was incorporated within the surface six inches of soil an application of 16 tons per acre of coarse organic matter (stable manure), it is seen that in the uncropped units the effect of the treatment is thus entirely a physical one, adding to the porosity of the surface-portion of the profile. In the cropped units, however, the effect of the treatment in addition to such physical effects is such as to further provide nutrients to the plants, which has resulted in some increased plant-growth. Such increase is found primarily in 1933 and 1935 when normal precipitation occurred, but not in the drought-years of 1934 and 1936.

Table 1--*Seasonal and annual amounts of runoff on a permeable soil under cropped and uncropped conditions, with and without organic-matter treatments*

Year	Period	Precipitation in inches	Amount of runoff in inches			
			Untreated units		Manured units	
			No crop	Cropped	No crop	Cropped
1933	May[a] to September	20.95	6.47	4.01	5.96	2.27
	May[a] to December	23.52	6.60	4.07	6.09	2.33
1934	May to September	14.45	4.74	2.21	3.67	2.43
	Year	23.62	7.92	4.45	6.00	4.40
1935	May to September	24.67	7.03	5.25	4.65	3.37
	Year	33.66	9.09	6.74	5.70	3.92
1936	May to September	14.70	4.54	2.94	2.99	2.15
	Year	21.61	5.86	3.91	3.66	2.54
Totals	May to September[b]	74.77	22.79	14.41	17.19	10.21
	1933[a]-1936	102.41	29.47	19.16	21.27	13.20

[a] Started May 1933. [b] Covering these months for 4-year period.

The runoff from the cropped units both for the growing season and for the entire period is much less than from the uncropped units. This is true both for the untreated and treated series. It is also true for each individual year and for the growing season of each year. Furthermore, it is corroborated in other experiments at the same Station where it has been found consistently

Fig. 1—

Relative losses of precipitation from a permeable and an impermeable soil, each with and without organic-matter treatments.

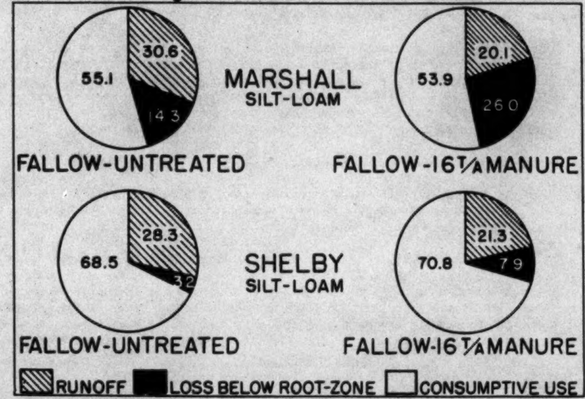
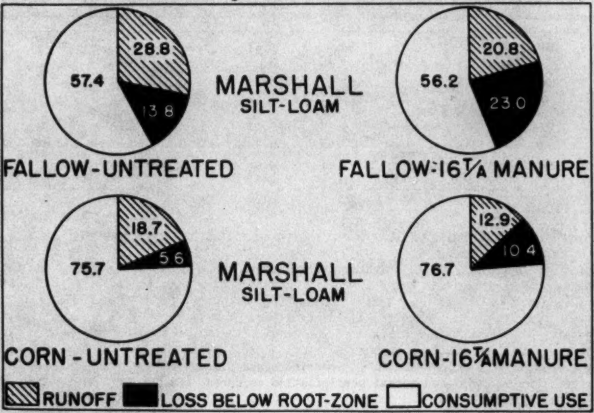


Fig. 2—

Relative losses of precipitation from a permeable soil under cropped and uncropped conditions with and without organic-matter treatments.



that runoff is less in the presence of a crop. Still further, it is commonly found that runoff is less on stubble land than on fallow land.

Amount of precipitation passing below the root-zone--In Table 2 are given the seasonal and annual amounts of precipitation passing below the root-zone of corn for the same treatments and units shown in Table 1. These quantities below a 3-foot profile are of much interest and significance. It is seen that the total seasonal and the total annual losses for both untreated and treated series is much less on the cropped units. With but one minor exception (the seasonal total for the drought-year of 1934) this difference holds true throughout the entire summary. In the untreated cropped units it is indicated that more than eight surface-inches of water has been intercepted in its course from the surface to the ground-water table. In the treated cropped units nearly 13 inches of water has been intercepted in its downward passage through the soil-profile.

Table 2--Seasonal and annual amounts of precipitation passing below the root-zone on a permeable soil under cropped and uncropped conditions, with and without organic-matter treatments

Year	Period	Precipitation in inches	Amount passing below root-zone in inches			
			Untreated units		Manured units	
			No crop	Cropped	No crop	Cropped
1933	May[a] to September	20.95	3.69	0.76	4.61	1.51
	May[a] to December	23.52	4.20	0.76	5.30	1.51
1934	May to September	14.45	0.06	0.15	0.16	0.13
	Year	23.62	1.07	0.15	2.43	0.19
1935	May to September	24.67	5.65	4.58	8.25	5.65
	Year	33.66	7.07	4.58	11.29	6.65
1936	May to September	14.70	1.43	0.28	3.18	1.51
	Year	21.61	1.82	0.28	4.49	2.29
Totals	May to September[b]	74.77	10.83	5.77	16.20	8.81
	1933[a]-1936	102.41	14.16	5.77	23.51	10.63

[a] Started May 1933. [b] Covering these months for 4-year period.

Vapor-loss--In Table 3 are given the seasonal and annual losses in the form of consumptive use from the same units as above cited. These figures are derived by subtracting the sum of the runoff and percolate from the total precipitation. As a calculation they are indicative of definite trends, but are not absolute values. Were it true that the moisture-content of the units at the end of the period was the same as at the beginning of the period, the results would represent precise values. On the basis of correlated moisture-studies at the same place in other experiments, it is indicated that such difference does not exceed 2.6 inches of water for the entire period and more probably has a value approximating 1/2 inch to 1.3 inches. This error of possible uncounted water represents but a small percentage of the total precipitation of 102.41 inches.

Table 3--Seasonal and annual amounts of vapor-loss on a permeable soil under cropped and uncropped conditions, with and without organic-matter treatments

Year	Period	Precipitation in inches	Amount of vapor-loss in inches			
			Untreated units		Manured units	
			No crop	Cropped	No crop	Cropped
1933	May[a] to September	20.95	10.79	16.18	10.38	17.17
	May[a] to December	23.52	12.72	18.69	12.13	19.67
1934	May to September	14.45	9.65	12.09	10.62	11.90
	Year	23.62	14.63	19.02	15.18	19.03
1935	May to September	24.67	11.99	14.84	11.85	15.65
	Year	33.66	17.50	22.34	16.85	23.10
1936	May to September	14.70	8.73	11.48	8.53	11.04
	Year	21.61	13.93	17.43	13.46	16.78
Totals	May to September[b]	74.77	41.16	54.59	41.38	55.76
	1933[a]-1936	102.41	56.78	77.48	57.63	78.58

[a] Started May 1933. [b] Covering these months for 4-year period.

On examining Table 3 it is seen that the total vapor-loss on the untreated series for the uncropped units is about 57 inches, while for the cropped units it is about 77 inches. The corresponding totals for the entire period on the treated units are very nearly the same as on the untreated. Thus, during the period of the experiment about one-half of the total precipitation has been lost in the form of evaporation from the uncropped units and about three-fourths of the total precipitation has been lost in the form of evaporation and transpiration from the cropped units. For the period under discussion the average annual difference between the cropped and uncropped units is about five inches of water.

In examining individual years it is seen that the manured and cropped units have used more water than the unmanured cropped units in the years approximating normal precipitation, but that during the drought-years there has been no increased consumption, due probably to the deficiency of water for plant-use.

Summary of losses from Marshall silt-loam--A summary of the total losses from these units is given in Table 4. Here the contrast between the cropped and the uncropped units in both series is apparent. Also the contrast between the treated and untreated units, particularly with reference to runoff and the losses below the root-zone, is striking.

Table 4--Summary of runoff, amount of precipitation passing below root-zone, and vapor-loss on a permeable soil under cropped and uncropped conditions, with and without organic-matter treatments

Losses	Treatment			
	Untreated units		Manured units	
	No crop	Cropped	No crop	Cropped
	inches	inches	inches	inches
Runoff	29.47	19.16	21.27	13.20
Amount passing below root-zone	14.16	5.77	23.51	10.63
Vapor-loss	58.78	77.48	57.63	78.58
Total precipitation	102.41	102.41	102.41	102.41

Tables 5, 6, and 7--Annual amounts of runoff, precipitation passing below the root-zone, and vapor-loss on uncropped permeable and relatively impermeable soils, with and without organic-matter treatments

Table 5--Amount of runoff

Year	Precipitation	Treatment			
		Untreated - fallow		Manured - fallow	
		Marshall	Shelby	Marshall	Shelby
	inches	inches	inches	inches	inches
1934[a]	13.97	6.23	4.88	4.74	4.66
1935	33.66	9.09	9.12	5.52	6.72
1936	21.61	5.86	5.58	3.66	3.36
Total	69.24	21.18	19.58	13.92	14.74

[a] Started July, 1934.

Table 6--Amount of precipitation passing below root-zone

1934[a]	13.97	1.02	0.18	2.21	0.34
1935	33.66	7.07	1.80	11.29	4.33
1936	21.61	1.82	0.22	4.49	0.79
Total	69.24	9.91	2.20	17.99	5.46

[a] Started July, 1934.

Table 7--Amount of vapor-loss

1934[a]	13.97	6.72	8.91	7.02	8.97
1935	33.66	17.50	22.74	16.85	22.61
1936	21.61	13.93	15.81	13.46	17.46
Total	69.24	38.15	47.46	37.33	49.04

[a] Started July, 1934.

Comparison of losses of a highly permeable and a relatively impermeable soil--There are available for comparison through a shorter period (2.5 years) the results from two different soil-types of which the diverse behavior with respect to water has been recognized. The infiltration-rate of the Marshall silt-loam is very greatly above that of the Shelby silt-loam and measurements of runoff from the two soils on field-scale plots have been shown to be correspondingly different. In Table 5 are given the annual amounts of runoff from the uncropped Marshall units above cited, in comparison with amounts from the relatively impermeable Shelby silt-loam. It is seen that in these units with a comparatively short length of slope there was no significant difference in the runoff on the two soils, although the incorporation of organic matter in the surface-zone has served very effectively to reduce the total amount of runoff.

Amount of precipitation passing below the root-zone--The annual amount passing below a 3-foot profile of undisturbed soil for each of these soil-types for the same units cited above are shown in Table 6. For the entire period on the untreated series nearly ten inches of water passed through the Marshall profile and somewhat more than two inches through the Shelby profile. In the treated series nearly 19 inches passed through the Marshall profile and about 5-1/2 inches through the Shelby profile. These differences in totals for the entire period hold true equally well with respect to individual years.

Vapor-loss--In Table 7 are shown the annual vapor-losses which in the case of these uncropped units is evaporation only. It is seen that the relative loss from the impermeable Shelby is much greater than that from the more open-structured Marshall. The difference between the two soil-types again is found for each individual year of both series. There may be several possible explanations for the greater evaporation from this impermeable soil. The coefficient of transference of heat may be greater in the tighter soil. Another possibility is that a larger proportion of the precipitation remains nearer the surface of the impermeable profile, and is thus susceptible to the immediate action of Sun and wind. Whether either or both of these explanations provide the correct answer may be open to question, but the fact remains that a significant and appreciable difference in evaporation has been found throughout the period of this comparison.

Other factors which affect precipitation-losses--There are obviously numerous factors which exert their effect upon the relative losses in the form of runoff, vapor, and movement below root-zone. Included among these are all of the effects of weather and climate, of vegetal cover in its entire range of density and vigor, and of the soil-medium in its complete range of chemical and physical properties. This paper presents data from the very specific but nevertheless highly significant conditions of two contrasting soils, with and without crop-cover and for both nearly normal and extremely deficient rainfall-conditions. The continuation of the work to extend into surplus moisture-conditions is essential.

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WATER-INTAKE OF SATURATED SOILS

W. C. Lowdermilk

Introduction

In his profound work "Data of geochemistry" Clarke accepts the estimate that of the total of about 337,000,000 cubic miles of water within the hydrosphere of the Earth, 29,347 cubic miles falls as precipitation on the land-area and 6,524 cubic miles returns to the oceans as streamflow annually [see 1 of references at end of paper]. Thus it appears that less than 0.002 per cent of the Earth's capital of water takes part in the ocean-land-ocean circulation. It is this small fraction of the Earth's store of water that has performed wonders throughout the sedimentary history of the Earth. It has been responsible for Nature's public works in sculpturing continents as they emerged from the oceans time after time throughout the ages.

Land-forms reflect the prevailing character and amount of precipitation and the work of runoff-waters. In a more specific way the formation of a coverage of soils and their interdependent mantles of vegetation is the response to temperature and precipitation and associated physical, chemical, and biological processes affecting land-sculpture.

The increasing population has quickened and intensified man's activities in bringing about changes on land-surfaces. In the past century, machines and power have been added to man's tools so that more wide-spread and significant changes have been wrought than were possible ever before. It is only in very recent times that the influence of human activities upon land and waters has become the object of scientific inquiry. Thus far only trends have been disclosed by researches in hydrology. In view of the growing conscious determination of peoples to make the land-surface a permanent and sustaining abode for human societies, it is well to refine the diagnoses of problems involved in sustained use of land and waters. Appropriate action waits on a correct diagnosis.

Such continued use of land is conditioned primarily on safeguarding the integrity of the soil-resource from wastage by erosion. Only thus may be assured a liberty of action in land-use responsive to progressive needs of a dependent people. And because of the part played by soils on the hydrologic cycle the sustained utility of water-resources is similarly affected. This much has become apparent. How to achieve such an objective is a question of high importance, and of intricate technical character.

The broad problem of diagnosis, which is twofold, may be simply stated. First, it consists in an evaluation of the several factors which determine the rate and amount of infiltration of waters into the land and, second, it comprises a determination of principles of hydraulics involved in leading unabsorbed meteoric waters harmlessly down to stabilized natural drainage-channels. In soil and water-conservation, therefore, infiltration is the more fundamental problem. It deserves our most thorough study looking to the development of land-use measures and practices suitable to sustained productivity of required food- and fiber-crops.

Horton [2] has recently furnished hydrologic science with a more thorough analysis, probably, of the infiltration of waters into soils than has thus far appeared. In this work the contributions of other students of the subject are brought to bear upon his treatment. It is the purpose of this paper merely to examine a single aspect of this complex problem, namely, the infiltration of water in saturated soils.

A misconception has arisen to which the writer has, I fear, contributed [4], that a saturated soil will absorb no more water--that the runoff from saturated soils except for evaporation will represent the total rainfall. This error in concept is obvious from a review of existing experimental data of runoff-, erosion-, and percolation-studies. The error is similar to that of the so-called sponge-effect of the forest. Many students of the comparative influence of forested and cultivated lands on runoff and flood-flows have likened the forest and its ground-cover to a sponge. The inference is that when the sponge is saturated all additional rain of a storm will run off the land into stream-channels. The experiments at Berkeley by the writer disclosed the error of this conception [5]; they established the important fact that under heavy rains the forest or vegetal litter is relatively unimportant in its capacity to absorb water; but is, on the other hand, fundamentally important in maintaining the soil-surface at its maximum rate of intake. Thus the soil-column is permitted to function to capacity in absorbing and transmitting water into lower layers. For, in the final analysis, the soil and underlying rock-formation above the zone of ground-water saturation is an enormous potential reservoir of meteoric waters. Accordingly, the baring of a soil formerly protected by a mantle of vegetation was found to reduce the rate of intake at the surface regardless of the capacity of the underlying soil-profile for percolation.

The soil and substrata above the water-table are second only to the ocean as a reservoir of waters. Meinzer [6] reports an average depth to the water-table of 37 feet based on data from 28,797 wells. The capacity of this zone of aeration exceeds the heaviest possible fall of rain and generally far exceeds total annual rainfall. Only in bottom-lands with ground-water near the surface or in table-lands underlain by ortestein amounting to unimportant percentages of total drainage-areas would such a generalization be incorrect. Generally, the land has the capacity to absorb all precipitation-waters directly if rates of intake were equal to rates of fall. It is the differential rates of supply and infiltration which create the problems of irregular runoff.

In the case of so-called saturated soils, the assumption is that during periods of prolonged rainfall the soil becomes "saturated" which by definition would destroy its capacity to absorb any additional water. In this sense the word "saturated" does not correctly describe the state of water in a soil--it is not static; it is dynamic. The water filling pore-spaces of the soil or underlying weathered material is in movement so long as gravitational forces upon it exceed capillary forces of retention.

Allowance must, of course, be made for perched water-tables which form above discontinuous impervious strata or lenses.

It seems desirable to find another term to define the condition of a soil fully charged with water when the rate of application exceeds the rate of effective infiltration. It may be necessary to resort to the use of a phrase to express this concept, such as a soil fully charged with water, or gorged with water, or dynamic saturation. Whatever expression is finally agreed upon, the distinction between the dynamic and static condition is necessary to reflect the true water-relations in a soil where the capacity for intake at the surface is greater than the rates of percolation downward through soil and underlying material.

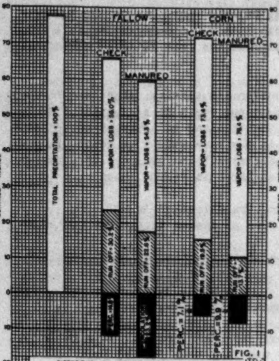


FIG. 1

DISPOSITION OF PRECIPITATION IN LYSIMETERS
MARSHALL SILT-LOAM MAY 1933 - NOV. 1935

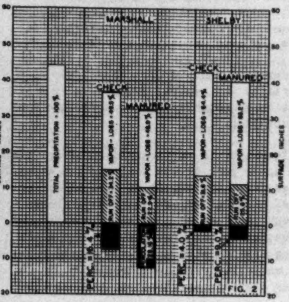


FIG. 2

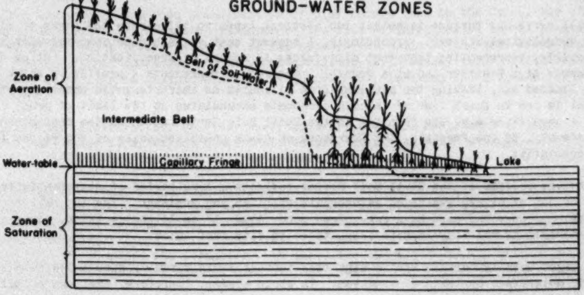
DISPOSITION OF PRECIPITATION IN LYSIMETERS
MARSHALL AND SHELBY SILT-LOAM
JULY 1934 - NOV. 1935

Factors of infiltration

Infiltration of meteoric waters into the land is conditioned first by rate of intake at the soil-surface and second by the rates of percolation through the soil-column and as well the underlying column of the zone of aeration. Horton has well said that the soil-surface acts as a sieve separating rainfall into surficial runoff and infiltration. It has been shown that the condition of the soil-surface is critical in such separations; this sieve may in effect be changed as to its size of openings. The change involves structural rather than textural modifications of the material. Under natural vegetation the structure of the soil includes macroscopic channels which remain open. The sieve under such conditions is in effect a coarse screen. But where soils are bared of natural vegetation, whether by fire, grazing, or cultivation, the natural macroscopic openings into the soil become clogged. And, furthermore, the soil-surface becomes a fine-mesh screen, even finer than the normal assemblage of soil-grains. The sorting of soil-particles in effect produces a sieve of finer mesh than the unmodified soil. The relative rates of passage of water through the surface are determined then by the size of openings of this soil-surface sieve.

This conclusion is founded on experimental evidence previously reported. Figures 1 and 2 show that two soil-masses placed in lysimeters in such a way that they represent like media of percolation, yielded strikingly significant differences in quantities of percolation as a result of different rates of intake by contrasted surface-conditions, where one was a soil covered with vegetal litter and the other a bare soil. In the former case, little or no erosion took place and the runoff-water was

FIG. 3—
GROUND-WATER ZONES



clear, whereas in the latter, heavy erosion occurred and the runoff-water was muddy with soil in suspension. The rate of percolation was conditioned by fineness of the sieve at the surface of the soil-column.

When the capacity for intake at the surface exceeds the rates of percolation through the soil-column into underlying material, the gorging of the soil with water becomes possible and will occur under prolonged rains. It is proper, then, to examine the factors which may affect percolation below the surface.

If a column of material in the zone of aeration were uniform in texture, size, and in structure, the rate of percolation under uniform heads and temperatures would be a constant. Rates of percolation could then be reduced to a simple formula. But the zone of aeration may present a multitude of conditions and combinations of conditions. It may vary widely in depth, in character and condition of material and zonation. Meinzer has differentiated the zone of aeration into three sub-zones as to the status of water. They are set forth in Figure 3 as:

(1) The soil, where soil-water is subject to evaporation- and transpiration-loss.
(2) Intermediate belt or vadose water-zone, where water is free of losses except through vapor-movement
(3) Capillary fringe, where soil-pores are charged with water held or drawn up under capillary forces.

In all cases, of course, water is subject to downward movement to ground-water.

Characteristics of the intermediate zone of aeration are dependent upon the original material and the state of jointing and weathering. The material may vary from jointed rock to sedimentary beds, with corresponding differences in both capacity to hold water and for percolation. Changes in this zone below the soil proper are slow; they involve weathering under conditions of alternate wetting and draining, giving place to hydration and oxidation. It is, moreover, in the soil-zone where important changes may and do take place, and require further consideration.

The soil-zone has in recent times been the object of detailed study under the science of pedology. It is only necessary to our purpose to review briefly the general principles of soil-formation which would affect percolation. The differentiation of material of the soil into horizons in itself has a profound influence upon rates of percolation.

The principal physical action in the process of soil-formation is the translocation or downward movement of the colloidal or clay-fraction out of the upper part of the soil and its deposition or accumulation in a lower horizon. Such action serves in a long period of time to differentiate the top soil from the subsoil. When this process of alluviation and illuviation have gone on undisturbed through time, especially in humid regions, the top soil or A-horizon becomes lighter or coarser in texture, and the B-horizon becomes heavier in texture, containing a greater percentage of clay. The B-horizon then normally would be tighter with a marked reduction in effective size of grains and pore-spaces. Its capillarity would be increased; therefore, it would have a capacity for holding more water but would offer greater resistance to percolation.

Thus the soil-forming or pedologic process is affected by climate, parent material, relief, and vegetation. Consequently, soil-profiles in the course of time develop differently. There are recognized the major soil-groups which Marbut has described for the United States [6].

It will serve our purpose to select two distinct types to illustrate the marks of widely different hydrological history. Accordingly, I suggest that a leached be compared with an unleached profile, representing important differences in amount of precipitation. Let us consider, then, a sample of a Pedalfer and of a Pedocal. The former represents a profile in which the bases are leached out, leaving the aluminum-iron silicates as characteristic material; whereas, the Pedocal is one in which lime or calcium carbonate accumulates at the limit of usual infiltration. A good example of the Pedalfer is the Cecil Soil-Series which is the predominant soil of the Piedmont. Of the Pedocals, the Chernozem or black grassland-soils of the Plains is a good representative.

The mature profile of the Cecil Soil-Series reflects a long period of differentiation of the horizons out of highly weathered metamorphic granites and gneisses. The top soil or A-horizon of the virgin or uneroded soil is a gray brown sandy loam, 10 to 14 inches thick, whereas the subsoil or B-horizon is red clay loam to clay, three to five feet thick.

This tight subsoil-horizon with a high clay-content would normally have a low rate of percolation as determined by textural fineness. It would appear, therefore, that the normal development of a soil-profile under such climatic conditions as prevail in the Piedmont would progressively reduce the rates of infiltration of the soil-zone. If the rainfall and type of intense storms should not change through time, it would be expected that the rate of surficial or storm-runoff would increase with consequent greater entrenching of streams and a more rapid rate of landscape-sculpture. Of course, such responses proceed at very slow rates but must be recognized as possible progressive changes which affect the hydrologic cycle, independent of climatic change.

Before proceeding with a discussion of a contrasting soil-profile, it is well to consider that under undisturbed conditions, it can be expected that the absorption-capacity of a soil under natural vegetation is an adjustment to the prevailing type of rainfall. Thus, the A-horizon would have a capacity to absorb the major quantity of waterfall of storms and that the natural vegetative surface-control is such that the soil-removal does not exceed the rate of soil-formation. We cannot escape these conclusions for if it had not been so, time enough has elapsed to have removed the soil to bed-rock.

Below the solum, as represented by the A- and B-horizons of the Cecil Series, occurs the C- and D-horizons. The C-horizon represents the weathered parent material which in the case of the Cecil is quite deep; it is granular, being a metamorphosed igneous complex in an advanced state of weathering. It is porous and transmits water by percolation at a much greater rate than the B-horizon. It will also crumble away and erode with great facility. Thus when gully-streams finally cut through the tough subsoil, they excavate this granular material to produce great "caves." They advance rapidly by undermining the subsoil-layers. The D-horizon represents the native rock. The C- and D-horizons pass downward to the water-table any waters which percolate through the solum proper.

In the case of the Cecil Soil-Series, the subsoil represents the principal barrier to percolation through the profile. This horizon consists of such fine material and is so compact that capillary forces limit transmission of water to very low rates. And if it were not for certain macro-structural features caused by root-penetration and animal and insect burrowing, the rate of intake of the Cecil beyond the capacity of the top soil would be reduced to an insignificant amount.

These considerations raise some interesting speculations. It would appear that the aging of a soil-profile will progressively reduce its rate of infiltration; and further that the soil-formation process, if given time enough, would bring about its own destruction by increasing the rate of storm-runoff and consequent land-sculpture.

Another typical soil-profile of distinctly different history and consequently of different character may be examined. A leached Pedocal horizon is selected for consideration. The Chernozem or black grassland-soil is a response through time of soil-development under grasses or grasslike-plants and under a climate of restricted rainfall. The supply of rainfall is insufficient to leach out the carbonates into the ground-water. Consequently, an accumulation of lime occurs as a lime- or carbonate-zone at the depth of usual infiltration. A record of the prevailing infiltration of precipitation-waters is thus written in the soil-profile itself. The depth of infiltration is affected by the amount and intensity of rainfall, by texture of the soil, by the transpiration of vegetation, and by the structure of the soil as induced by the fibrous annual roots of grass-vegetation.

In the Chernozem, much less translocation of clay occurs than in the Cecil, for example. Hence, no conspicuous clay B-horizon is formed. The rate of infiltration is not progressively reduced by soil-forming processes as may be the case in the soils of the gray-brown podzolic groups. The structural character of the black grassland-soils rather favors infiltration and percolation; it is high in organic content; it is columnar, inviting the deep and rapid penetration of water.

The zone of calcification, or lime-layer, however, presents resistance to rapid percolation to deeper layers if an excess of rainfall occurs, or if the water storage-capacity above this layer is reduced by removal of soil in erosion.

These two strikingly different soil-profiles are the product of distinctly different combinations of conditions of which the water-supply doubtless plays the major role, providing the temperature-factor is approximately the same. The prevailing hydrological responses are reflected in these profiles. It is certain that under natural conditions the removal of soil-material by erosion has not exceeded its formation. In fact, the wastage under the protection of natural vegetation must have been very slow to have allowed time for the prolonged soil-forming processes to have differentiated the soil into distinct zones of removal (A-horizon) and accumulation (B-horizon).

The hydrology of a soil-profile is thus affected in an important way by the soil-building process; but it may be influenced in as profound a way by the action of plant-roots and of animal life.

Root-penetration by natural vegetation must play an important part in the transmission of water through tight subsoils. Decaying roots leave channels throughout the root-zone. Roots of oak trees were found in eastern Nebraska by J. E. Weaver and Joseph Kramer to have penetrated to a depth of 14 feet with an average of ten feet. The tall grass-roots penetrated to an average depth of eight feet in the same region.

In the Piedmont the long-leaf pine was found to have a tap-root penetration of about ten feet with the longest being fully 15 feet. Short-leaf pine tap-roots were found to have penetrated the soil to an average depth of five to six feet up to eight or nine feet as the maximum. Roots of the oaks in the same region showed an average penetration of five to six feet. These depths extend well into and sometimes through the B-horizon or subsoil. Thus, the lacework of decayed root-channels may well serve to conduct water through a soil-horizon that otherwise would permit a slow rate of percolation because of its textural composition.

The findings of Joffe [3] in his lysimeter-studies seem to support such a conclusion. It was found, for example, that percolation through the B- and C-horizons of the soils of New Jersey, where the experiment was located, took place along cracks, root-channels, and such openings. The percolation from the lower A-horizon into B- and C-horizons was not important.

Animal life may be even more important than plant-roots in the hydrology of a soil-profile. Micro-organisms play an important role in the breaking down of organic matter, in the nutrition of plants, and upon soil-structure. These influences, however, would affect rapid movement of water to a less degree than the macro-organisms.

A host of animal life is found in soils, from crustacians, earthworms, myriopods, insects, spiders, to rodents and larger mammals. The influence and importance of the excavations, burrowings, and the resulting effect upon the movement of water under saturated conditions has scarcely been touched. Such activities of animal life within the soil would be at its maximum in soils covered with natural vegetation.

The activities of soil-burrowing animal life serves to plow or cultivate the soil throughout its profile. Channels are formed, pockets of loose soil, and food-caches and voids are left in the soil. How much these conditions resulting from animal activity within a soil may affect the infiltration-rate is little known. More study of this subject is highly desirable.

Grinnell concludes that pocket-gophers in California by their burrow-systems hasten the weathering of the subsoil, favors water-intake, enhances fertility and buries vegetable material deep within the soil, thus contributing to its productivity for natural vegetation. Darwin's classic study would indicate that activity of the earthworm has an important effect upon infiltration.

These considerations have to do with soils under natural vegetation and in their virgin condition. But soils must be cleared and cultivated. The effect of continued cultivation upon the rates of infiltration and percolation becomes a matter for special consideration and study. Attention has already been called to the effect of the baring of a soil upon the rate of intake. It is the place now to consider further the effect upon percolation of water through the profile of a cultivated soil.

In some soils a plow-sole develops to form a compacted pan six to eight inches below the surface. This plow "hardpan" retards the rate of percolation of water at that level. The comparatively shallow layer of plowed soil becomes the immediate and limited reservoir for rain. When the fall exceeds this capacity, further intake is limited by the reduced rate through the layer of hardpan.

Cultivation of the soil introduces a number of other important conditions in the soil-profile. The removal of trees or grass-cover removes the action of deep penetrating roots. In time, decayed root-channels are filled with soil-material, eliminating the channels and voids existing within an uncultivated profile. The transition from natural to cultivated condition may be pronounced in the case of shallow-rooted cultivated crops, or less so in that of deep-rooted crops such as cotton.

In a similar but perhaps lesser degree the activities of animal life are reduced. The plowing of soil destroys each time such burrowings and helps to fill the channels and burrows below the plowed zone. The aggregate effect of cultivation is to reduce the lace-work of channels and burrows within a soil which would favor infiltration of water under saturated conditions; it makes the soil more homogeneous; it favors the trapping of air within the soil under heavy rains. Trapped air in a freshly-plowed field, for example, can markedly reduce infiltration. The general effect of cultivation, then, is to reduce the rate of intake and the rate of infiltration of water into the zone of aeration. Percolation becomes more nearly a function of the texture of the soil-material, rather than of the macro-structural features of a profile arising from actions of roots and living organisms.

Summary

It becomes apparent that the hydrology of the soil-profile may be influenced by soil-formation processes and by both plant- and animal-action within the soil. Information on these subjects in quantitative terms is very meager. There is thus room, in this important part of ocean-land-ocean circulation, for profitable studies of the factors affecting the infiltration of waters in soil-columns and underlying material. "Saturation" of the soil is only a relative term; its use has given rise to the erroneous conception that no further infiltration will occur from a saturated soil, whereas, in fact, the condition is a dynamic saturation and permits water-movement through the soil-column. Since the capacity of the zone of aeration is far in excess of any given storm, storage of heavy precipitation is conditioned upon the rate of infiltration into the soil. The degree to which rates of infiltration may be restored or increased becomes an important hydrological problem.

Future research on infiltration is indicated and it should yield the following data:

(1) The infiltration-rates of each of the horizons in the soil-profile without regard to the underlying or overlying layers.
(2) The influence of macro-structures on rates of infiltration.
(3) The magnitude of changes wrought by cultivation.

From these data, a curve may be drawn for a soil which would chart the water-movement through the soil and substratum. This phase of the problem of ocean-land-ocean circulation would thus be subject to solution.

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THE RATE OF INFILTRATION OF WATER IN IRRIGATION-PRACTICE

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(The data reported in this paper have been secured in the course of irrigation- and drainage-investigations conducted, during 1926 and 1927, by the Idaho Agricultural Experiment Station and, since 1932, by the Oregon Agricultural Experiment Station, both in cooperation with the United States Bureau of Agricultural Engineering.)

Introduction

The rate of infiltration of water into soil is a problem of paramount importance in irrigation, drainage, flood-control, and soil-erosion. Heretofore most studies on the rate of movement of water through soils have had to do with movement through saturated material. Recently attention has been given to the maximum intensity of rainfall which will be absorbed by soil without surface-runoff, or the rate at which absorption takes place when the rate of fall is in excess of the absorbing capacity of the soil. The latter case approaches most nearly the conditions encountered in irrigation.

The length of time during which water should be held on the surface of land and, therefore, the length of irrigation-furrows or border-strips and the size of irrigation-streams, is fixed by the quantity of water required to replenish the soil-moisture supply and the rate of infiltration. Whenever new land is brought under irrigation the rate of infiltration which may be expected should be considered in planning the system of water-delivery, the farm distribution-system, and the preparation of the land for irrigation.

Too often scant attention has been paid to this factor and local customs have been followed, or extensive projects have been developed on a uniform plan regardless of wide differences in soils. Heretofore application of infiltration-rates to irrigation-design has been worked out by trial and error in the field after the irrigation-system has been completed or has been dependent on the judgment of the engineer or farmer. The studies herein reported were made in an attempt to work out a method by which the design could be based on some comparatively simple tests of soils which could be made in advance of irrigation-development.

Water infiltrates into the soil by gravity and in addition, under ordinary irrigation-practice, by capillary attraction. Where the soil and subsoil are uniform or the subsoil is more permeable than the surface-soil and the water-table is well below the surface, the rate of infiltration appears to be controlled at or very near the surface. Where the subsoil is less permeable than the surface, the surface-layer soon becomes saturated and the subsequent rate of infiltration is governed by the subsoil. In effect a perched water-table occurs. Under such conditions the rate of infiltration is relatively great at first and falls off rapidly when the surface-soil becomes saturated.

The rate of infiltration is, of course, dependent primarily on the permeability of the soil and numerous measurements of permeability have been made in the laboratory. Lewis and Neal [see 2 of references at end of paper] used a series of tanks of different diameters about 30 inches deep filled with surface-soil, and determined the rate at which water was absorbed. There are two serious objections to this method. The structure of the soil, including such larger openings as caused by drying and worm- and root-holes, is destroyed and generally its porosity is altered. The result is an entirely different soil-mass than occurs in the field. Also, all effects of the subsoil below the depth sampled are lost.

Powell [10], Slater and Byers [12], and others have met the first of these objections by taking soil-cores to various depths without materially disturbing the structure. The convenience of having the soil-samples in the laboratory for testing is considerable, but the difficulty of securing undisturbed samples, even with the improved types of sampling cylinders, is great enough to nearly, if not entirely, overcome the advantage of inside work with the samples. Moreover, the effect of any less pervious layer below the depth sampled is lost.

No data are available to prove that the rate of infiltration into a uniform soil-column is affected by the length of the column. However, the water-holding capacity of a column is certainly affected by its length and it seems probable that the rate of infiltration may also be affected. The effect of the capillary moisture-gradient should be similar in the two cases.

To some extent this difficulty could be met by the method used by Piper [9] and others in field-capacity or specific-retention measurements. However, the direct measurement of the rate of infiltration in the field seems the most satisfactory. Under most conditions this may be done by the use of rings or open-ended cylinders set a short distance into the soil.

This method was extensively used by workers [4, 5, 6] in France in conjunction with tests in the laboratory of the permeability of the soil. Muntz and his coworkers noted that in most instances the rate of infiltration was most rapid when water was first applied and then decreased rapidly for a time, generally a few hours, after which flow took place at a steady rate. They used this steady rate of flow as the measure of the permeability of the soil and devised a scale of permeability, the unit being a depth of one centimeter infiltrated per hour. They experimented with irrigated soils with permeabilities ranging from 0.1 or 0.5 at Fourcadel to 50 or 60 at Valence. These figures correspond to rates of 0.0006 or 0.003 to 0.33 or 0.4 inch per minute, respectively.

In some areas the subsoil is less permeable than the surface-soil. As is pointed out by Musgrave [7], the rate of infiltration in the field is governed by the least permeable horizon. Cylinders set only a few inches into the soil may not measure the permeability of the subsoil. Musgrave met the condition by forcing his cylinders down to the less permeable B-horizon by means of jacks. His results with two soils indicate a decreasing rate of infiltration during the first portion of the 6-hour period for which data are reported. In studying infiltration-rates in connection with soil-erosion, he is particularly interested in minimum rates. In irrigation-practice, particularly on sandy soils, we are more interested in maximum rates.

Experimental data

Open cylinders or rings were first used by the author in 1926 for measuring the rate of infiltration on the Idaho Agricultural Experiment Station at Moscow and Caldwell, Idaho. The following paragraphs are taken from the report for that year to the Director:

"Six galvanized rings 1.25 feet wide and 1.5 feet in diameter (area 1.767 square feet) made of 20-gage galvanized iron were secured. These rings were set in the ground to a depth of three or four inches with earth tightly packed around the outside. Water in weighed amounts was then poured into the rings, and the time required for it to disappear noted. Fresh water was then applied and the time noted. Two objections to this method may be mentioned. On pouring the water into the ring the softened surface-soil was disturbed so that any skin-effect was broken up. Also this erosion left the surface of the soil uneven so that water stood in small depressions long after it had disappeared from most of the surface. Water from the open drain-ditch was used for these tests.

"The data for these trials were plotted on logarithmic paper. It was found that the points plotted in such fashion that straight lines could be drawn representing very well the points for each individual test. Considering the preliminary nature of the trials and the two difficulties mentioned above, the nearness with which the plotted points approach such straight lines seems very remarkable. On the basis of this plotting it appears that the depth of water absorbed bears a definite relation to the time during which water is held on the surface. This relationship is expressed by a formula of the form $y = ct^n$, where y = depth of water infiltrated in inches, t = time of infiltration in minutes, c = a coefficient varying in these trials from 0.031 to 0.16, and n = an exponential factor varying in these trials from 0.24 to 0.7.

"Data for a number of trials are shown on Figure 1 herewith. It appears to be possible to draw rather interesting conclusions from these curves. For instance, the spading of the soil in trials 8 and 11 gave an opportunity for greater initial infiltration but had little effect on the rate after the first few minutes. The black alkali seemed to have a depressing effect on initial infiltration but gives, after the initial period, a rate intermediate between that on the bare spots and on the spots supporting a good stand of clover.

"Assuming the accuracy of these formulae, it follows that the rate of infiltration at any given moment may be determined from the first differential of the equation for depth of infiltration. The formula is of the form $i = cnt^{n-1}$, where i = rate of infiltration in inches per minute, t = time elapsed since water was applied in minutes, and c and n have the same values as in the corresponding formulas for depth."

The soil is a recent sedimentary "classified as Caldwell loam by the Bureau of Soils in field-operations of 1901 and later correlated as the Elsinore series."

It is believed that the differences noted both in the growth of sweet clover and in the rate of infiltration for rings 3, 14, and 5 are accounted for by differences in the alkali content of the soil rather than that the rate of infiltration has been affected directly by the growth of clover.

A test made at Moscow on Palouse silt-loam in an old orchard with a matted growth of bluegrass resulted in data which can be represented by the formulas $y = 0.58t^{0.87}$ and $i = 0.50t^{-0.13}$.

Some objection has been made to the use of this method for determining the rate of infiltration in the belief that the water, upon reaching the lower edge of the ring, spreads laterally. It has been contended that the larger area through which flow thus takes place makes possible an abnormally high rate of infiltration. J. C. Marr (unpublished reports) made comparisons in 1926 and in 1927 at Caldwell to test this factor. In 1926 he kept two plots of about one-sixth acre flooded and noted the rate at which water infiltrated. At the same time he kept graphic water-stage recorders over 18-inch rings on adjoining plots. The results are shown in Figure 2. It will be noted that the rate of infiltration was extremely slow on all plots and that except for the trial on plot 12 the rate decreased for the first two or three days and then became uniform. The plots were in a single row so that plots 3 and 4 and 11 and 12 were adjacent. The rate and depth infiltrated and the location in the field of numbers 4 and 11 (18-inch ring tests) were intermediate between 3 and 12 (flooded-plot tests). So far as the data go, they indicate that

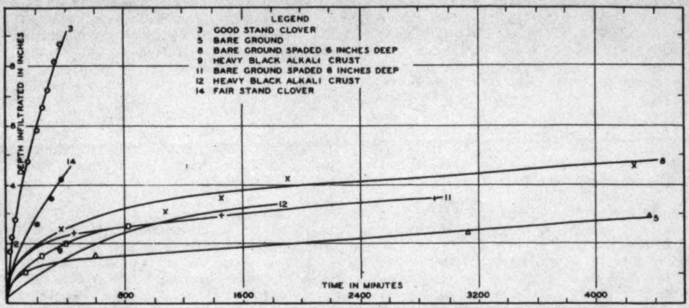

FIG. 1—INFILTRATION-TRIALS WITH 18-INCH RINGS ON ELSINORE LOAM CONTAINING DIFFERENT QUANTITIES OF ALKALI AT CALDWELL, IDAHO

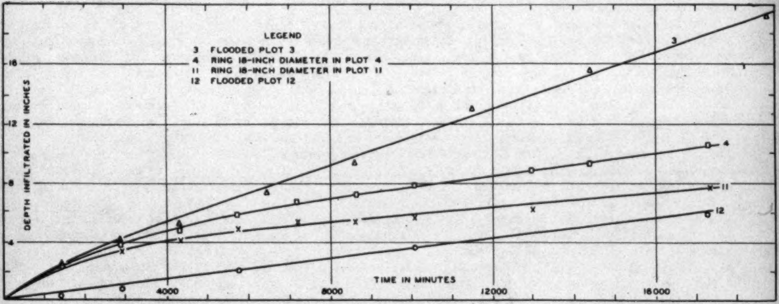

FIG. 2—COMPARISON OF INFILTRATION-RATES FROM 18-INCH RINGS AND FLOODED 1/8TH-ACRE PLOTS ON ELSINORE LOAM AT CALDWELL, IDAHO

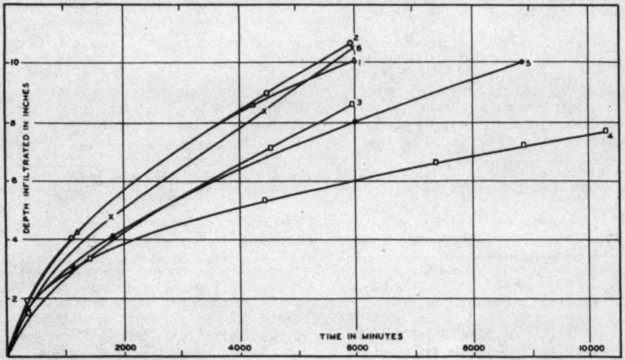

FIG. 3—COMPARISON OF INFILTRATION-RATES FROM AN 18-INCH CYLINDER SET 7 FEET IN GROUND (2) AND FROM 18-INCH RINGS ON ELSINORE LOAM, CALDWELL, IDAHO

the 18-inch rings give results comparable to those of flooded plots.

In 1927 tests were made with 18-inch diameter cylinders. One cylinder, however, was seven feet long and was placed without disturbing the soil inside it. This ring extended through the 4.4 feet of soil and clay-subsoil and 2.6 feet into the underlying gravel. The data for the test are shown in Figure 3. Cylinders 1 and 3 were on opposite sides of cylinder 2 (the long one) and 18 feet distant. Cylinders 4, 5, and 6 were 118, 218, and 318 feet distant, respectively, from cylinder 2. All but cylinder 2 were 15 inches long and set three or four inches only into the soil. The relatively slow rate for cylinder 4 is believed to be due to its proximity to a permanently-saturated plot in an adjoining series. These data again show a decreasing rate of infiltration. The rate of infiltration for cylinder 2 is fully as rapid as for any of the other cylinders, and again the data indicate that the use of cylinders set a few inches into the soil gives reliable results.

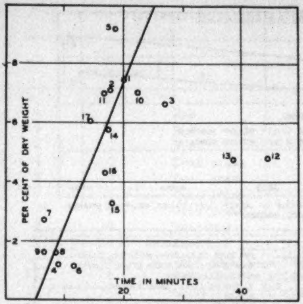

FIG. 4—RELATION BETWEEN TIME REQUIRED TO INFILTRATE 2 INCHES OF WATER AND MOISTURE-CONTENT OF UPPER FOOT OF EPHRATA LOAMY SAND, UMATILLA FIELD-STATION, HERMISTON, OREGON

In 1933 the following experiment was conducted on the Umatilla Field Station at Hermiston, Oregon. The soil is a loamy sand resting at depths of three to five feet on a partly cemented gravel. A cylinder 18 inches in diameter and a section of 6-inch pipe were used. Each was 12 inches long. In each trial the 6-inch pipe was centered inside the 18-inch cylinder.

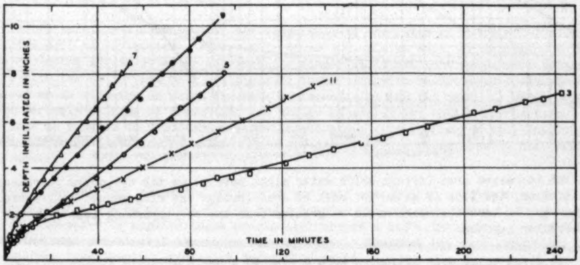

FIG. 5—INFILTRATION-TRIALS WITH 18-INCH RINGS ON EPHRATA LOAMY SAND AT DIFFERENT POINTS, UMATILLA FIELD-STATION, HERMISTON, OREGON (SEE TABLE 1)

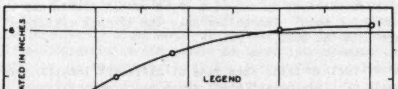

FIG. 6—INFILTRATION-TRIALS WITH 18-INCH RINGS ON TWO SOIL-TYPES, ONE BOTH WET AND DRY, AGRICULTURAL EXPERIMENT-STATION, CORVALLIS, OREGON

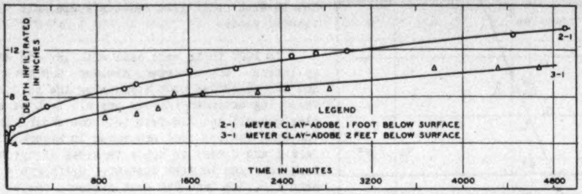

FIG. 7—INFILTRATION-TRIALS WITH 18-INCH RINGS AT TWO DEPTHS ON MEYER CLAY-ADOBE, MEDFORD BRANCH EXPERIMENT STATION, MEDFORD, OREGON

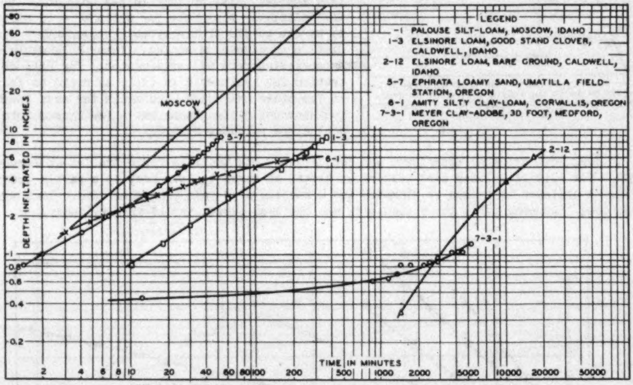

FIG. 8—COMPARISON OF INFILTRATION-RATES ON DIFFERENT SOIL-TYPES

If the increased area through which water might move below the cylinders increased the rate of infiltration, the loss of water per unit of area through the ring-shaped soil-surface between the 6-inch and 18-inch cylinders would be greater than the corresponding loss from the inner 6-inch circular surface.

In the first trial both cylinders were driven to a depth of three inches only and it was found that the rate was greater from the outer ring than from the inner circle. In the second and third trials the cylinders were driven to a depth of six inches and the rate of infiltration was found to be the same for both. Thereafter only the 18-inch cylinders were used and they were driven six inches into the soil.

In 1935 a number of further tests were made at different locations on and near the station. Table 1 shows the length of time the different plots had been irrigated, the vegetative cover at the time of the tests, the initial moisture-content and apparent specific gravity of the top foot of soil, and the time required for the infiltration of two inches of water. There appears to be little, if any, correlation between the rate of infiltration and the length of time the plot had been irrigated, the type of vegetation, or the apparent specific gravity, but there is a definite relationship between the rate of infiltration and the moisture-content of the top foot of soil. This relationship is shown in Figure 4. The curves of Figure 5 show the data for several tests. These results show a decreasing rate of infiltration for a short time and thereafter a constant rate.

Tests have been made on Amity silty clay-loam and Chehalis loam at Corvallis and on Meyer clay-adobe at Medford. Results of some of these tests are shown on Figures 6 and 7. On the Meyer clay-adobe the results obtained with rings driven six inches into the soil were useless as the water moved laterally through cracks. The data shown on Figure 7 for this soil are for the second and third feet below the surface.

Table 1--Infiltration-tests on the Umatilla Field-Station

No.	Time irrigated	Vegetation	Initial moisture-content	Apparent specific gravity	Time for infiltration of 2 inches
	years		per cent		minutes
1	1	Rye	7.4	....	20.0
2	1	Rye	7.1	1.66	18.0
3	1	Rye	6.6	....	27.3
4	0	Dead grass	1.2	1.57	9.1
5	0	Dead grass	9.2	1.57	18.6
6	0	Dead grass	1.2	1.57	11.3
7[a]	0	Dead grass	2.6[b]	1.53	6.9
8	0	Dead rye	1.6	1.63	8.7
9	0	Dead rye	1.6	1.63	7.0
10	4	Bare spot in alfalfa	7.0	1.68	22.8
11	4	Bare spot in alfalfa	7.0	1.68	17.2
12	4	Heavy stand of alfalfa	4.8	1.57	44.8
13	4	Heavy stand of alfalfa	4.8	1.57	39.0
14	2	Dead rye	5.8	1.72	17.6
15	2	Heavy stand sweet clover	3.3	....	18.2
16	2	Heavy stand sweet clover	4.3	....	17.0
17	2	Dead rye	6.1	1.66	14.8

[a] Test made with top foot of soil removed.

[b] Values for second foot, all others for first foot.

In order to show the extreme range in the rates and depths of infiltration found with different soils, Figure 8 has been prepared.

It is believed that these measurements are comparable to the rates at which water will infiltrate into the soil in irrigation. Powers [11] is of the opinion that air confined in the soil below an advancing stream of water may markedly hinder infiltration. He reports trials in the laboratory with two soil-types both artificially packed and with undisturbed field-structure in tubes 3 to 15 cm in diameter in which the rate of percolation and the depth to which moisture percolated was markedly reduced by preventing the escape of air at the bottom of the tube. It would appear that if this is an important factor, infiltration from furrows or small cylinders would be more rapid than from flooded areas. Marr did not find this to be true in his trial in 1926 reported above.

Fortunately even the less permeable soils when dry will absorb fair amounts of water. Mathews [3] reports that the heavy soil on the Belle Fourche Project will crack on drying and that when irrigation-water is applied these cracks will absorb a light irrigation before they swell shut and the soil practically ceases to take up water. Somewhat the same conditions are found on the Medford Experiment Station with Meyer clay-adobe.

The time required for the proper irrigation of a strip-border or other irrigation-unit is primarily dependent on the rate of infiltration. Almost all of the data reported herein indicate a much more rapid rate immediately after water is applied than later. This fact is of considerable importance in irrigation-practice and should be taken into account in studies of the application of water. Muntz and his coworkers [4, 5, 6], Parker [8], and Israelsen [1] all treat the rate of infiltration as a constant for any one set of conditions. Recognition of the fact of its variability assists in explaining field-results in irrigation.

There has been a great deal of discussion of the excessive use of irrigation-water on sandy soils and of the difficulty of getting sufficient penetration of water on very heavy soils. The extremes illustrated in Figure 8 readily explain the practical difficulties. To apply a light irrigation of three inches to the Meyer clay-adobe subsoil or the bare Elsinore loam requires a period of six to 12 days, while the Palouse silt-loam or the Ephrata loamy sand will absorb the same quantity of water in as many minutes. Data of this kind for the soils of a project in advance of irrigation-development would be of immense value in planning the distribution of irrigation-water to the farms and on individual farms.

Summary

(1) The rate of infiltration of water into the soil is of paramount importance in irrigation as well as in other fields.

(2) There is need for a method of determining this rate in advance of irrigation-development in order that field-ditches and irrigated fields may be properly designed.

(3) Measurements of the rate and depth of infiltration should be made in the field.

(4) Small cylinders (18 inches in diameter) were used and were shown to give reliable results.

(5) Tests of the rate of infiltration on several different soils at different locations in Idaho and Oregon are reported.

(6) Depths infiltrated ranged from 0.48 inch to 20 inches at the end of one hour and from 0.53 inch to 80 inches at the end of five hours.

(7) The more rapid infiltration at the beginning of an irrigation should be considered in the design of irrigation-field layouts.

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DIRECT ACCRETIONS TO GROUND-WATER FROM RAINFALL

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Direct penetration of rainfall to the ground-water has long been recognized as an important source of many ground-water supplies. This subject, with the results of experiments begun in 1833, was discussed in the Proceedings of the Institute of Civil Engineers in 1850 [see 1 of references at end of paper].

The portion of the rainfall which penetrates to the ground-water is the residual item after all other uses of rainfall have been met. It is the part of the rainfall which is absorbed by the soil and not used as plant-transpiration or soil-moisture evaporation. Such deeply penetrating rainfall is equivalent to the permanently absorbed water as defined by Lee [2]. Direct accretions to ground-water from rainfall, as the term is used herein, is limited to such accretions from the area on which the rain falls. Even with small amounts of rainfall there is always some concentration of runoff in low areas from which some deep penetration may occur. This may be an important item in some areas; it is small on flat areas, for small rains or on coarse soils.

Deep penetration of rainfall depends upon the moisture-content of the soil at the time the rain occurs. Rainfall that is absorbed in land increases the moisture-content of the soil to its capillary capacity. Except for very heavy single storms or on areas of high ground-water, rainfall does not move downward in the soil as gravity flow but as moisture near or somewhat above the field capillary capacity. Absorbed moisture moves downward readily to the depth to which it can raise the soil-moisture to its field-capacity; further downward movement may continue if the lower soil is dry but will take place at a much slower rate. In the meantime such absorbed moisture is subject to use by the plants and, near the surface, to soil-moisture evaporation. Soil-moisture under conditions in the field never reaches a state of equilibrium but is continually subject to changes in its amount by inflow and draft and to changes in its position by movement as capillary or gravity flow. Any moisture passing below the depths from which plant-roots may secure it will eventually reach the ground-water whether such movement occurs as gravity or capillary flow.

The results of many observations on rainfall-penetration have been expressed in terms of the percentage of the rainfall reaching the ground-water. While this is a convenient form of expression, it has only a limited usefulness in comparing results under different conditions. The same rainfall may result in widely differing percentages of penetration where conditions vary. For the same locality and soil the percentages of penetration in different years may vary widely.

These factors and their effects can be illustrated by the results of observations under different conditions. Much work in this field has been done in areas having sufficiently different conditions so that it is now possible to forecast the general result to be expected.

In England long-continued observations at Rothamsted [3] and other stations [4, 5, 6, 7] have shown such penetration to be a major item in the ground-water supply. The difference in penetration with similar rainfall in the chalk-areas as compared with other soils has been recognized. The large amounts of penetration during the winter when plant-use is reduced is also shown. Certain minimum amounts of rainfall are required before any penetration occurs; for larger rainfalls the proportion of penetration increases rapidly.

Results in other European countries have been quoted in several publications in English [5, 8, 9]. These have generally been expressed as a percentage of the annual rainfall. They indicate larger percentages with larger rainfall and for coarser soils.

Observations in India are consistent with those elsewhere. Work at Cawnpore [10] and Pusa [11] showed large amounts of penetration during the months of the rainy season. The rainfall in some periods was sufficiently heavy to obscure the effect of plants and as large penetration occurred on the cropped lysimeters as on fallow soil.

In the United States work on rainfall-penetration has included lysimeter-observations, field soil-moisture measurements, and general balances of items of inflow and outflow for drainage-areas. Among the earlier extensive investigations were those on Long Island [8] in connection with the water-supply of the City of New York. Relatively large amounts of penetration were found with an annual rainfall of over 40 inches on these generally sandy soils. Larger penetration occurred with smaller rainfall during the winter months than during the summer growing months. General studies in the Pomperaug Basin [12] in Connecticut and extensive lysimeter-experiments at Cornell [9, 13] gave similar general results.

In the semiarid area little penetration has been found except on sandy soils. The contrast between results on different soils is shown by the inability of moisture to penetrate the gumbo-soils at Belle Fourche [4] and the runoff of the Loup River which drains mainly sandhill areas in western Nebraska. The Loup River has a well-sustained runoff of about 150 acre-feet per square mile per year coming mainly from the percolation to the stream-channels of deep penetration from the 23 inches of mean annual rainfall. Streams draining other Great Plains areas having heavier soils have generally less total runoff per square mile with little, if any, sustained low-water flow. Observations in Nebraska [15, 16] on medium to heavy soils have shown that with annual rainfalls of about 28 inches occurring largely in the months of plant-growth, there is practically no penetration of moisture below the roots of annual crops. Work in North Dakota [17] indicated that rainfall did not penetrate below five feet on cropped land and eight or nine feet on fallow. If permanently fallowed, deep penetration would result in time. Experiments at Umatilla, Oregon [18], have shown the effect of plants in intercepting and using downward moisture-movement where frequent light irrigations were applied.

Work by the Division of Agricultural Engineering of the United States Department of Agriculture [19, 20] in Southern California, where rainfall occurs mainly in the semi-dormant winter months and where the soils are dry at the end of the summer depletion-period, has shown that deep penetration depends on the extent of the initial soil-moisture deficiency, the depth of plant-roots, and the character and sequence of the individual storms. Concentration of rainfall that supplies the soil-moisture deficiency and results in moisture-movement below the plant-roots before it is used for transpiration is essential to deep penetration. Much larger amounts of rainfall were required to cause deep penetration on deep-rooted brush than on areas in grass or weeds.

From these results the factors which control rainfall-penetration and the conditions favorable to relatively large amounts of such penetration can be recognized.

(1) The amount of rainfall-penetration cannot be estimated on the basis of the mean annual rainfall alone.
(2) In any locality penetration will vary widely from year to year and may occur only in years of above-average rainfall.
(3) Coarse-textured soils permet penetration under some conditions where no penetration would occur with heavier-textured soils.
(4) Shallow-rooted crops permit larger amounts of penetration than deeper-rooted crops.
(5) The time of the year during which the rainfall occurs materially affects the amount of penetration. Rainfall during periods of plant-dormancy is most effective.

Applying these conclusions to the conditions in the United States, contributions to the ground-water from direct penetration of rainfall would be expected in the eastern states from the usual annual precipitation of 30 inches or over even on the heavier soils with larger penetration on sandy areas.

In the Great Plains Area with 15 to 25 inches of mean annual rainfall, material amounts of rainfall-penetration would be expected only under particularly favorable conditions. Prior to settlement, most of this area was covered with relatively shallow-rooted sod. The prevalence of the sod instead of brush or trees is an indication of the lack of rainfall-penetration. This condition should be considered in any plans for ground-water development in these areas. While there may be considerable amounts of accumulated ground-water under these lands, the rate of any local recharge is relatively slow and extensive ground-water draft can only be expected to result in rapid depletion.

In the arid areas rainfall-penetration would be limited to that occurring in areas of accumulated runoff such as ponds or along stream-channels.

In Pacific Coast areas rainfall-penetration is larger than would be expected from the same general annual average rainfall in other areas owing to the concentration of the rainfall in the winter months of semi-dormancy of plants. Conditions for penetration are particularly favorable in many parts of Southern California where large areas of coarse alluvial fill receive sufficient rainfall in winter to result in an amount of deep penetration which represents an important part of the local water-supplies.

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DETERMINATION OF INFILTRATION-CAPACITY FOR LARGE DRAINAGE-BASINS

Robert E. Horton

Introduction-synopsis--This paper describes a method which may be used for determining the average infiltration-capacity over a drainage-basin during large storms where a runoff-record, together with adequate rainfall-data, are available. The application of the method requires that in each drainage-basin there shall be at least one rain-intensity record kept with a recording rain-gage. The metnod is based on the observed fact that in great general storms, while there may be two or more different types of rain-intensity graphs in different parts of the storm-area, locally the rain-intensity graphs are statistically very much alike.

Two general cases are considered:

(1) Where the rain-intensity rises for a time above the infiltration-capacity of the soil in all parts of the drainage-area, so that the entire drainage-basin contributes runoff. This is designated a "full-area flood" or stream-rise.

(2) Where the rain-intensity on part of the area does not at any time rise to a point equal to the infiltration-capacity, so that part of the area does not contribute runoff. This is designated a "partial-area flood."

The methods described in the paper are applied to two general cases:

(1) The New England flood of November 2-5, 1927.

(2) A series of stream-rises on each of the following streams: Delaware River, Embarrass River, Wabash River, French Broad River, Susquehanna River, and Muskingum River.

The infiltration-capacities are least for the rocky and mountainous basins of the French Broad, Delaware, and upper Susquehanna rivers. For the latter basins the infiltration-capacities range from minima in spring and fall of 0.05 to 0.10 inch per hour to maxima in July and August of 0.30 to 0.40 inch per hour. For the generally flatter, permeable basins of the Wabash, Embarrass, and Muskingum rivers, the soil is largely of glacial origin and mostly under cultivation. Infiltration-capacities range from spring and fall minima of 0.15 to 0.30 inch per hour up to maxima of 0.80 to 1.20 inch per hour. Values close to the spring and fall minima may occur in midsummer if the soil is wet and rain-packed from recent antecedent rains.

Taken together there are shown (1) infiltration-capacities on many different areas in the same storm, (2) infiltration-capacities in several different storms on the same drainage-basins. The determinations of infiltration-capacity in the New England flood range from 0.05 inch per hour in the rocky and mountainous upper Connecticut Basin to 0.56 inch per hour in the highly permeable Quinebaug Drainage-Basin.

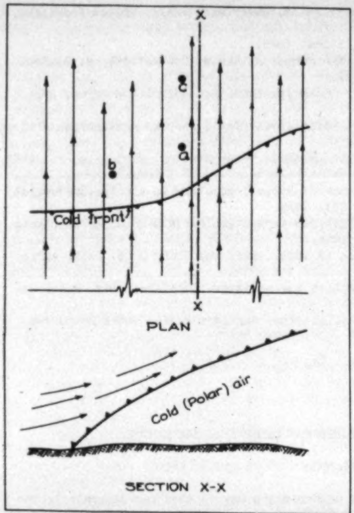


FIG. 1 - RELATION OF STATIONARY COLD FRONT TO DURATION OF STORM-RAINFALL

All of the determinations have been platted so as to show the seasonal march of infiltration-capacity. This is a maximum in August and the infiltration-capacity during midsummer storms is usually around a maximum value, ranging, in the examples given, from about 0.6 to 0.9 inch per hour or else it is close to the minimum value of about 0.1 inch per hour. Both the seasonal march of infiltration-capacity and the absolute values determined from these large drainage-basins are in good agreement with values of infiltration-capacity derived from laboratory and runoff-plat experiments and from smaller areas.

Meteorologic basis--The basis of the determination of infiltration-capacity in this paper is the fact that surface-runoff approximately equals the difference between the rainfall and the infiltration during the part of the storm in which the rain-intensity exceeds the infiltration-capacity. This difference is called the rainfall-excess or total supply.

The determination of infiltration-capacity f consists in finding a value of f such that the product of f and the duration of rainfall at intensities in excess of f subtracted from the total rainfall for the same interval will leave a remainder equal to the surface-runoff.

Since rainfall-records must be used which for the most part give only the total amount of rainfall, the determination of infiltration-capacity involves the problem of determining the hourly rain-intensity distribution at such stations. It is assumed that at least one record of hourly rain-intensity is available. This is called the base-station. If the duration of rainfall is the same and the rain-graphs are statistically similar at the base-station and at an adjacent station, the hourly distribution of rainfall at the second station may be obtained by multiplying the ratios of hourly to total rainfall at the base-station by the total rainfall at the second station. This is precisely the same as the use of the unit-graph method for distribution of runoff, although this method was applied to rainfall by the author 20 years earlier.

Application of this method requires that the time-bases of the rain-graphs at adjacent stations shall be approximately equal but not necessarily simultaneous. This is usually not true of local storms of the convectional type, as has been shown by Thornthwaite [see 1 of references at end of paper]. It may not be true of general storms where the cold front or fronts move rapidly. Unless correction is made for varying rain-duration in the manner subsequently described, the use of the method should be limited to general storms with nearly stationary cold fronts.

Since the impression prevails that rain-intensity distribution is highly erratic and uncertain, it is important to discuss briefly the characteristics of rain-intensity graphs in general storms.

Dr. C. F. Brooks [2] has recently pointed out that in general two conditions are necessary to the production of a major storm: (1) The existence of one or more stationary or nearly stationary high-pressure areas, with accompanying cold fronts; (2) the existence of an adequate supply of warm, moist air flowing up the faces of the air-mountains produced by the cold fronts.

Differences in amount of rainfall in the same storm and adjacent to the same cold front may be due to (1) difference of rain-intensities, (2) difference of rainfall-duration, (3) both combined. Consider a great storm with a more or less stationary cold front, as shown schematically in plan and section by Figure 1. Two adjacent rainfall-stations may be either: (1) Similarly situated relative to the cold front, as a and b; (2) located on the same stream-line or line of air-flow but at different distances from the cold front, as a and c; (3) differently situated relative to the cold front, as in case of b and c. Except as modified by topographic conditions, stations a and b will in general have similar rain-intensity graphs but with some difference on duration of rainfall, especially if one station is near the center, the other near the edge of the warm air-current. Stations a and c will in general have nearly the same rainfall-duration but are likely to show large differences in rain-intensity and total amount. All stations controlled by this particular cold front will therefore show, in general, statistically similar rain-intensity graphs, with small or moderate variations in total duration of rainfall, these differences increasing with distance between the stations. Two or more fronts are often involved in the same storm, in which case the characteristics of rainfall in the rain-smear controlled by the different cold fronts may be widely different, but, for stations controlled by a given front, the assumption that the duration of rain is similar at two adjacent stations will usually be nearly true. This is clearly shown by Table 1, which shows total duration of rain and intensity at recording rain-gage stations subject to control by the eastern and western cold fronts, respectively, in the New England storm of November 2-5, 1927.

Table 1--*Storm rainfall, New England flood of November 2-5, 1927*

Station (1)	Rainfall-duration, hours (2)	Total rainfall, inches (3)	Average hourly intensity, inches (4)	Maximum hourly rainfall, inches (5)
		Western cold front		
Albany, N. Y.	40	3.86	0.0965	0.31
Burlington, Conn.	33	5.51	0.167	0.50
Hartford, Conn.	38	3.57	0.094	0.44
New Haven, Conn.	31	3.78	0.122	0.53
New York, N. Y.	32	1.63	0.057	0.27
Northfield, Vt.	43	8.63	0.201	0.62
Springfield, Mass.	39	4.28	0.110	0.55
West Hartford, Conn.	36	3.92	0.109	0.35
Monroe, Mass. (a)	36	6.20+	0.172	0.35
Shelburne Falls, Mass. (a)	26	3.80+	0.146	0.38
Whitingham, Vt. (a)	34	5.51+	0.162	0.38
Somerset, Vt. (a)	22	8.47+	0.385	0.65
Vernon, Vt. (a)	27	3.73+	0.138	0.35
		Eastern cold front		
Blue Hill Observatory, Milton, Mass.	18	2.16	0.120	0.45
U.S. Weather Bureau, Boston, Mass.	18	1.81	0.100	0.41
Brookline, Mass.	13	1.33	0.102	0.28
Concord, N. H.	15	4.03	0.269	0.80
Eastport, Me.	11	3.14	0.286	0.77
Lowell, Mass.	12	3.26	0.272	1.04
Pawtucket, R. I.	14	2.24	0.160	0.35
Portland, Me.	11	0.75	0.068	0.25
Providence, R. I.	14	1.26	0.090	0.25
Hope Reservoir, Providence, R. I.	15	1.57	0.105	0.32
Winter Hill Observatory, Worcester, Mass.	18	4.26	0.237	0.68
Sewage Plant, Worcester, Mass.	19	5.10	0.268	1.42

(a) Initial rain omitted; duration exceeded number of hours in column (2); maximum intensity is average for highest two hours.

Determination of storm-rainfall--It is assumed that the surface-runoff (that is, total runoff minus ground-water) is known. The next step is the determination of rainfall-stations to be included and the total storm-rainfall at each. The Thiessen-Horton method [3] furnishes an accurate criterion for determining stations to be included in calculating the mean rainfall on a given area for any storm or time-interval. In general, all stations within the basin should be included, together with those outlying stations which would be included if the Thiessen-Horton method was applied. This can be determined quickly by inspection.

Determination of storm-rainfall at a given station is complicated by the fact that rainfall is not recorded at the same hours. Climatological Data, published by the United States Weather Bureau, gives the times of reading at United States Weather Bureau stations. These times are usually either 8 to 9 a.m. or 5 to 6 p.m. at voluntary stations, and midnight at regular stations. The rain recorded on a given date is that which fell in the 24 hours preceding the time of reading. With the list of stations there should be set down the times of observation. The days of record to be included or excluded at a given station can then be readily determined from the record at the recording gage or base-station in the manner illustrated by the following example.

Suppose, for example, at the recording station, the storm lasted from 6 a.m. to 11 p.m. on May 10. There was no antecedent or subsequent rain on May 10 or 11. Therefore, at other stations the records to be included are the recorded amounts for May 10 and 11, whether the reading was taken in the morning or afternoon, since in both cases the rain began before and continued after the time of observation on May 10.

If, on the other hand, the storm had begun at 10 a.m. and ended at 4 p.m. on May 10, and there had been antecedent rain, then obviously at stations where readings are taken in the morning the amount recorded on May 10 should not be included, and rain in any shower between 4 p.m. and the next 8 a.m. of the following morning, and recorded on the 11th, should not be included. For stations where readings are taken in the evening, if there was no antecedent rain, all rain recorded on the 10th should be included, but nothing included which was recorded on the 11th.

Suppose in the last case the storm which produced the stream-rise lasted from 10 a.m. to 4 p.m. on the 10th, but there was another shower from 3 to 7 a.m. on the 11th.

Consider first a station where readings are taken in the morning. The record on the morning of the 11th includes both showers and the amount to be included at a given station may be taken as the same proportion of the total recorded amount as the amount which fell in the first shower is to the total rain during the same 24-hour period at the base-station. If the reading was taken in the afternoon, the recorded rain on the 10th should be included, and that on the 11th excluded.

Determination of infiltration-capacity for full-area stream-rises--In detail the method used in this paper is as follows. For full-area stream-rises, a first approximation to the infiltration-capacity is obtained by subtracting the total runoff, after deducting ground-water flow, from the total rain at the base-station, and dividing the remainder by the duration of rainfall at the base-station. On large areas two or more base-stations may be used if available, each one being applied to rainfall-records at the nearest adjacent station. The percentage of total storm-rainfall which fell in each hour during the storm is first determined for the base-station.

Next, assuming a total rainfall of some number of even inches about equal to the average storm-rainfall on the given area, the hourly distribution of rainfall for this total amount of rainfall is computed by multiplying each of the hourly ratios at the base-station by the assumed rainfall. Next, assuming a series of infiltration-capacities varying by tenths of an inch and ranging from a value below to a value considerably above the trial value of f, the excess of rainfall is computed by subtracting the infiltration-capacity from the corresponding hourly amounts of rainfall if the latter are greater. This computation for a rainfall of four inches, distributed as shown by the recording rain-gage record at Vernon, Vermont, in the November 1927 flood is shown in columns (5) to (9) of Table 2. The sum of the items entered in the column corresponding to a given infiltration-capacity will then represent the excess of rainfall corresponding to a given assumed rainfall. Similar computations are made for other assumed total amounts of rainfall varying by even inches from the lowest up to the highest amount of rainfall occurring at any station within the drainage-basin. In this instance the computations are made for Millers River at Erving, Massachusetts. It will be noted from Table 2 that for a storm-rainfall of four inches there would be no excess of rainfall and hence no surface-runoff on the part of the drainage-basin with an infiltration-capacity of 0.4 inch per hour or more.

The total amounts of rainfall-excess for different assumed storm-rainfalls and infiltration-capacities are then plotted as shown on Figure 2. From the curves given on Figure 2, the excess of rainfall for various infiltration-capacities can be determined for any total amount of rainfall. The total storm-rainfall is tabulated for all stations applicable to the given drainage-basin and storm, as shown in column (6) of Table 3. The corresponding amounts of rainfall-excess are then taken off for each assumed infiltration-capacity and set down in columns (7) to (9), inclusive. The average of the determinations in any given column represents the average excess of rainfall over the drainage-basin. These averages are plotted in terms of the infiltration-capacity in Figure 3. The total surface-runoff at Erving in the November 1927 flood was 2.26 inches and, as shown at a of Figure 3, the corresponding infiltration-capacity f is 0.116 inch per hour.

Table 2--*Rainfall-excess, based on Vernon, Vermont, recording record for storm of November 3, 1927*

Record at Vernon, Vermont			P = 4.0 inches					
Hour	Amount, inches	Portion of total	Total amount, inches	Infiltration-capacity f, inches per hour				
				0.10	0.20	0.30	0.40	0.50
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
				Rainfall-excess				
5 a.m.	.05	.013						
6	.05	.013						
7	.03	.008						
8	.02	.005						
9	.05	.013						
10	.05	.013						
11	.07	.019						
12 m.	.08	.022	.088	0				
1 p.m.	.20	.054	.216	.116	.016	0	0	0
2	.20	.054	.216	.116	.016	0	0	0
3	.13	.035	.140	.040	0	0	0	0
4	.12	.032	.128	.028	0	0	0	0
5	.03	.008						
6	.02	.005						
7	.15	.040	.160	.060	0	0	0	0
8	.15	.040	.160	.060	0	0	0	0
9	.35	.094	.376	.276	.176	.076	0	0
10	.35	.094	.376	.276	.176	.076	0	0
11	.35	.094	.376	.276	.176	.076	0	0
12 p.m.	.35	.094	.374	.276	.176	.076	0	0
1 a.m.	.25	.068	.272	.172	.072	0	0	0
2	.25	.068	.272	.172	.072	0	0	0
3	.15	.040	.160	.060	0	0	0	0
4	.15	.040	.160	.060	0	0	0	0
5	.05	.013						
6	.05	.013						
7	.02	.005						
8	.01	.003						
Totals	3.73	1.000		1.988	.880	.304	0	0

Table 3--*Rainfall-excess for different assumed infiltration-capacities, Millers River at Erving, Massachusetts, flood of November 2-5, 1927 (rainfall-intensity base-station, Vernon, Vermont)*

Station, Massachusetts	November, 1927				Total rainfall, inches	Infiltration-capacity f, inches per hour		
	2	3	4	5		0.10	0.20	0.30
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
						Total rainfall-excess		
Wendell		1.81	4.10	0.12	5.91	3.65	2.22	1.27
Warwick	1.37	2.08	0.36		3.81	1.82	0.77	0.20
Fitzwilliam	1.19	2.24	0.33		3.76	1.76	0.74	0.18
Winchendon	0.91	3.80	0.33		4.13	2.08	0.95	0.35
Baldwinsville	0.42	3.62	0.39		4.01	2.00	0.90	0.30
Gardner		4.06	0.03		4.09	2.05	0.93	0.33
Athol	1.00	4.83	0.09		4.92	2.76	1.48	0.74
New Salem			6.05	0.05	6.05	3.77	2.32	1.35
Averages					4.58	2.49	1.26	0.590

This method of procedure is direct and exact so far as determination of average excess of rainfall is concerned, provided the data are adequate. As regards determination of average infiltration-capacity, it is subject to the following qualifications:

(1) The term "runoff" as here used refers to surface-runoff. It is assumed that a ground-water depletion-curve has been obtained from records of the stream-flow, and the ground-water flow has been eliminated from the runoff-graph. It is assumed that the surface-runoff equals the rainfall-excess. Surface-runoff cannot, however, occur unless there is water standing on the ground-surface. This may be merely a film so thin as to be barely perceptible. When rainfall-excess ends there is always a certain amount of residual detention which continues to contribute surface-runoff for a short time. Part of this surface-detention is lost by infiltration, so that if there was no residual rain after rainfall-excess ends, surface-runoff would always be somewhat less than rainfall-excess. There is, however, always some residual rain at intensities less than infiltration-capacity, part of which is contributed to surface-runoff, so that actually the surface-runoff ranges from values a little less than to values a little greater than the total rainfall-excess or supply. In general, the error resulting from the assumption that rainfall-excess or supply and surface-runoff are equal is relatively small.

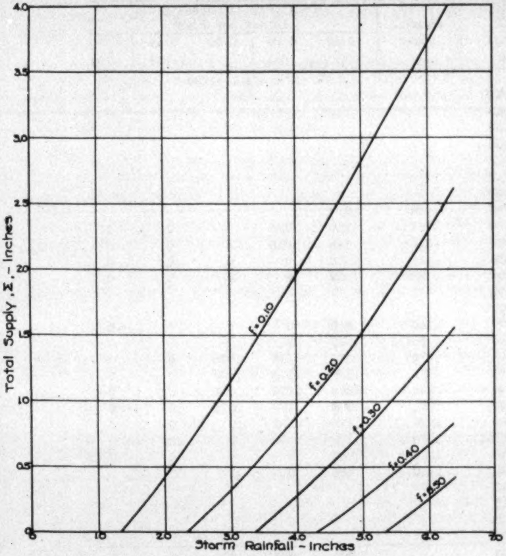


FIG. 2 - RAINFALL-EXCESS CURVES FROM VERNON, VT. RECORDING-GAGE RECORD FOR STORM OF NOV. 3, 1927. MILLERS RIVER ABOVE ERVING, MASS.

(2) A second qualification arises from the fact that infiltration-capacity may vary in different parts of the drainage-basin. This will have little effect on the accuracy of the determination of average infiltration-capacity if the rain-intensity exceeds the actual infiltration-capacity on every part of the area. In general, the method is applicable only in cases where this is true.

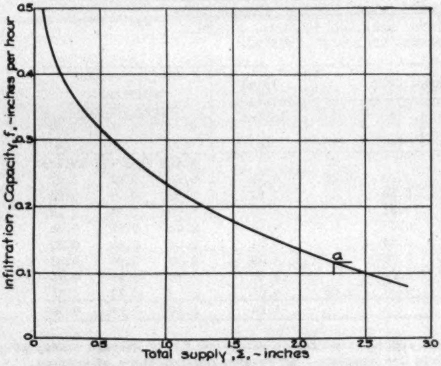


FIG. 3 - TOTAL-SUPPLY CURVE; STORM OF NOV. 2-5, 1927; MILLERS RIVER ABOVE ERVING, MASS.

It is of course possible to weight the individual determinations of rainfall-excess by the Thiessen-Horton method. This is somewhat laborious and does not add materially to the accuracy of the result if the rainfall-stations are (1) uniformly distributed or (2) if there are eight or more stations appurtenant to the given area.

In the determinations of infiltration-capacity given in this paper a direct average of rainfall-excess was used. Subject to the exceptions noted, the number of rainfall-stations was sufficient to give an accurate result without weighting. The exceptions are the drainage-basins mostly in Maine and New Hampshire, in the November 1927 New England flood. For some of these basins only two to five rainfall-stations were available. For these basins there may be considerable error in the computed infiltration-capacity.

Extension to varying rain-bases--The method described is capable of extension to cases where the rain-base is not the same at adjacent stations provided there are available three recording rain-

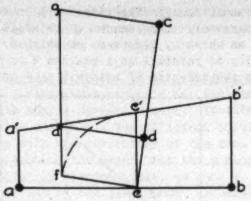


FIG.4 - DETERMINATION OF RAINFALL - DURATION

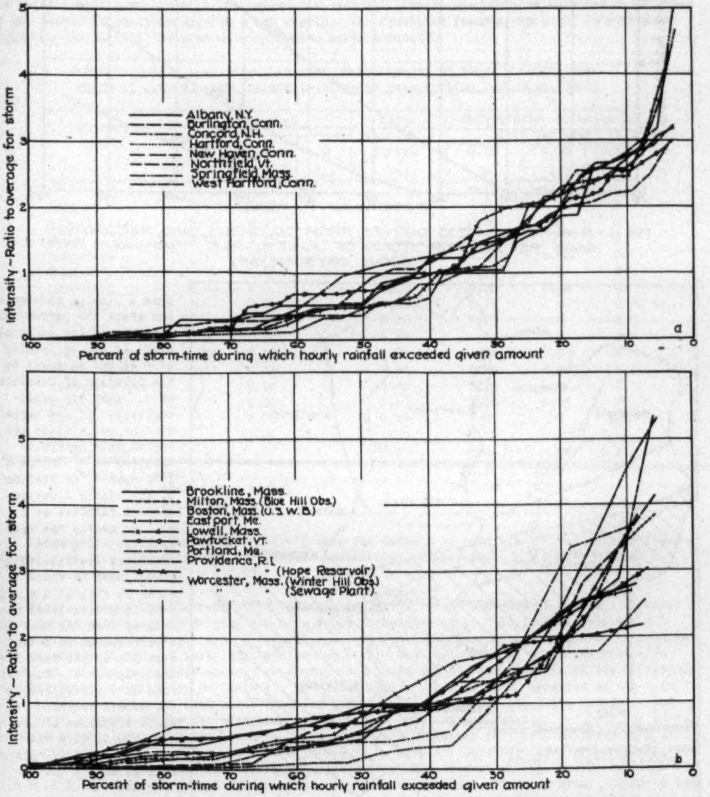


FIG.5 - RAIN-INTENSITY DISTRIBUTION-GRAPHS FOR NEW ENGLAND FLOOD, NOV. 2-5, 1927
(a)-WESTERN COLD FRONT (b)-EASTERN COLD FRONT

gage records at stations not too remote from the region under study. The first step is to determine the approximate duration of rainfall at stations where only total amount of rainfall is given. This is accomplished by the inclined-plane method, as shown by Figure 4, on which a, b, and c are the locations of recording rain-gages. The duration of rainfall at a station d is to be determined. Erect ordinates aa' and bb' proportional to the duration of rainfall at a and b. Draw a line ce through d and erect the perpendicular ee' and tne perpendiculars ef and cg, making ef = ee' and cg equal to the duration of rainfall at c. Then the scale-equivalent of the perpendicular dd' will be the approximate rainfall-duration at d. Since d lies nearest to station b, the hourly distribution of rainfall at d will be nearly the same as at b. If a rain-intensity distribution-graph, such as those shown on Figures 5-a and 5-b, is available at station b, then one hour at b corresponds to a fraction 1/n of the base of the graph at b. The total rain at d multiplied by the middle ordinates of n equal divisions of the base b will give the hourly amounts of rainfall at d.

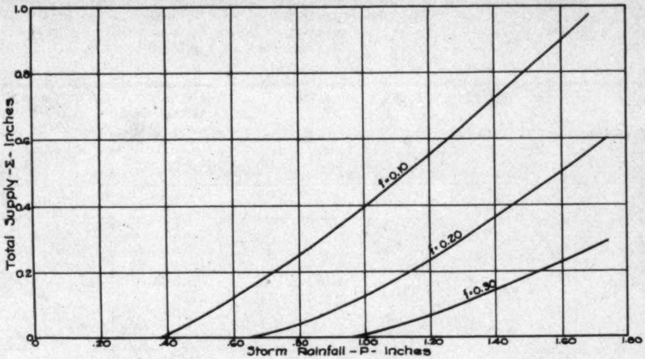
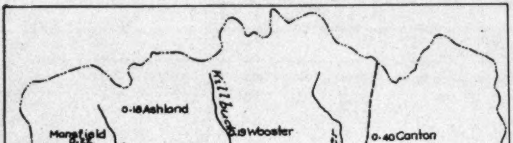


FIG. 6 - RAINFALL-EXCESS CURVES FROM COLUMBUS, OHIO, RECORDING-GAGE RECORD FOR STORM OF JUNE 8, 1929, MUSKINGUM BASIN ABOVE DRESDEN, OHIO


0.18 Ashland
Mansfield 0.22
0.19 Wooster
0.40 Canton
Killbuck
Walhonding
River
Creek
0.55 Bangorville
0.30 Millersburg
0.40 Dover
0.84 Mt. Vernon
Walhonding 0.80
River
0.58 Dennison
Tuscarawas
Coshocton
Newcomerstown
Cadiz
N
Wills Creek
0.72 Cambridge
1.30 Zanesville
-scale-
0
10
20
30
40 miles

Note - Effective area (42%) which produced runoff is shaded

FIG 7 - MUSKINGUM RIVER BASIN ABOVE DRESDEN, OHIO RAINFALL FOR STORM OF JUNE 8, 1929

Correction for varying duration of rain has not been made in this paper. In case of the New England flood the duration of rain was unusually constant in each of the two controlling storm-areas. In case of the other areas adequate recording rain-gage records were not in general available.

Extension of method to partial-area stream-rises--In case the rain-intensity does not exceed the infiltration-capacity for any single hour at a given rainfall-station, there will be no net supply and no surface-runoff. If this condition exists it will at once appear in the table of computed net supply for different infiltration-capacities. In this case it is necessary to determine both the percentage of the area which produced runoff and the infiltration-capacity on the same part of the area. For the purpose of showing the method of procedure, the rise of Muskingum River at Dresden, Ohio, on June 8, 1929, has been used. The computation of supply-curves is carried out in the same manner as before and these curves, using Columbus as the base-station, are shown on Figure 6. The total rainfall and the computed net supply at the different stations are shown on Table 4. Column (6) shows zero net supply or runoff at four stations for f = 0.10. The total significant items in the column for each infiltration-capacity is obtained and divided by the number of stations showing a net supply. The resulting figures represent average net supply on the part of the area which produced surface-runoff.

Table 4--*Supply Σ on effective area, Muskingum River above Dresden, Ohio, storm of June 8, 1929 (rainfall-intensity base-station, Columbus, Ohio)*

Station, Ohio (1)	June, 1929			Total rainfall, inches (5)	Infiltration-capacity f, inch per hour		
	7 (2)	8 (3)	9 (4)		0.10 (6)	0.20 (7)	0.30 (8)
					Total rainfall-excess		
Ashland		0.18		0.18	0	0	0
Bangorville	0.28	0.27		0.55	0.09	0	0
Cadiz	0.51	0.11		0.62	0.13	0	0
Cambridge		0.72		0.72	0.20	0.02	0
Canton		0.40		0.40	0.01	0	0
Coshocton	0.80			0.80	0.25	0.04	0
Dennison		0.58		0.58	0.11	0	0
Dover		0.40		0.40	0.01	0	0
Mansfield		0.22		0.22	0	0	0
Millersburg	0.03	0.27		0.30	0	0	0
Mount Vernon	0.41	0.43		0.84	0.28	0.06	0
Newcomerstown		0.66		0.66	0.16	0	0
Walhonding		0.80		0.80	0.25	0.04	0
Wooster (No. 1)		0.19		0.19	0	0	0
Zanesville		1.30		1.30	0.64	0.30	0.11
Averages				0.57	0.19	0.09	0.11
Percent of area					65.5	30.0	
Runoff from whole area, inches					0.05	0.05	
Runoff from net area, inches					0.076	0.167	

The supply-curves, Figure 6, for $\Sigma = 0$ show the amounts of rainfall for which the net supply would be zero with different infiltration-capacities. These are: f = 0.1, p = 0.38; f = 0.2, p = 0.65; and f = 0.3, p = 0.97.

Figure 7 shows the observed storm-rainfall at the different stations of record. On this map a dashed rainfall-contour-line has been drawn corresponding to 0.38 inch of rain and 0.1 inch infiltration-capacity. Also a rainfall-contour (dotted line) has been drawn corresponding to 0.65-inch rain and 0.2-inch infiltration-capacity. The percentage of the total area with greater rainfalls than these amounts were next determined and set down underneath the corresponding infiltration-capacities on Table 4. The total runoff was 0.05 inch, measured on the total area, but all this runoff took place from the part of the area having requisite rainfall, and the runoff, reduced to the net effective area for each infiltration-capacity, is next set down in Table 4. The supply on the net area corresponding to different infiltration-capacities is then plotted in the same manner as before in Figure 8, line A. Line B is also drawn showing the percentage of the area which yielded runoff with different infiltration-capacities, together with line C, showing corresponding depths of runoff reduced to net effective area. Opposite the intersections of lines A and C will be found the infiltration-capacity f for which the supply on the net area will equal the runoff-depth from the net effective area. Also opposite the same point on line B will be found the percentage of the total area which produced runoff. From

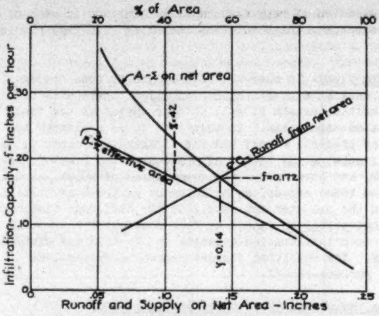


FIG. 8 - DETERMINATION OF INFILTRATION-CAPACITY ON EFFECTIVE AREA FOR STORM OF JUNE 8,1929, MUSKINGUM BASIN ABOVE DRESDEN, OHIO

Figure 6 the rainfall corresponding to zero-supply for this infiltration-capacity can be determined and a contour drawn (solid line) on Figure 7 which shows the part of the area which produced runoff during this stream-rise. This gives, finally, an infiltration-capacity f = 0.172 inch per hour on 42 per cent of the area.

Infiltration-capacity in the New England flood of November 2-5, 1927--The New England storm of November 2-5, 1927, involved two high-pressure areas, one northeast of New England, the other over and west of the northern Appalachians. These remained fairly stationary for several days, and between these was a barometric trough or "squeeze" into which flowed large volumes of moist, warm, tropical air.

TABLE 5-AVERAGE INFILTRATION, NEW ENGLAND BASINS, FLOOD OF NOV. 2-5, 1927

No. (1)	Stream (2)	Location (3)	Drainage-Area (4)	Base Rainfall-Intensity Station (5)	No. of Rainfall-Stations used (6)	Crest-Discharge (7)	Surface-Runoff on Area (8)	Mean Rainfall on Drainage-Area (9)	Infiltration Capacity (10)
	Penobscot Basin		Sq. Miles	Eastport, Me.		C.S.M.	Inches	Inches	Inches/Hr.
1	Penobscot	W. Enfield, Me.	4690	"	7	13.0	1.50	2.49	0.145
2	E. Br. "	Grindstone, "	1070	"	4	19.9	1.88	2.56	.082
3	Mattawamkeag	Mattawamkeag, "	1500	"	4	11.3	2.07	2.39	.058
	Piscataquis Basin								
4	Piscataquis	Lows Bridge, Me.	286	"	3	23.6	1.20	2.14	.135
5	"	Medford, "	1170	"	4	15.6	1.47	2.53	.152
6	Pleasant	Milo, "	325	"	3	22.4	2.54	2.89	.035
8	Dead	The Forks, "	830	"	3	17.7	1.15	3.36	.39
9	Carrabassat	N. Anson, "	351	"	2	53.0	2.89	2.94	.026
	Saco Basin								
15	Saco	Cornish, Me.	1300	Concord, N.H.	7	8.3	1.91	4.39	.285
18	Ossipee	" , "	455	"	4	5.1	1.18	4.38	.415
	Merrimack Basin								
19	Pemigewasset	Plymouth, N. H.	599	Northfield, Vt.	4	100.0	5.28	5.18	.028
22	Merrimack	Franklin Jct., "	935	Concord, N. H.	5	71.6	4.34	5.26	.091
33	Smith	Bristol, "	78.5	"	2	74.0	3.23	6.08	.315
34	Nubanusit	Peterboro, "	54.3	"	2	18.6	1.94	4.17	.25
35	Contoocook	N. Branch Village, "	54.5	"	3	38.6	3.21	4.51	.13
37	Souhegan	Merrimack Village, "	168	"	3	39.7	2.62	3.87	.128
38	Blackstone	Worcester, Mass.	31.5	Worcester, Mass.	3	25.0	2.72	3.85	.15
41	Quinebaug	Jewett City, Conn.	712	"	3	17.5	1.46	4.54	.565
	Connecticut Basin								
43	Connecticut	South Newbury, Vt.	2750	Northfield, Vt.	14	28.4	3.22	4.28	.052
45	"	White River Jct., "	4040	"	21	36.6	3.91	5.13	.058
47	"	Turners Falls, Mass.	7170	"	27	23.8	3.21	4.94	.063
48	"	Sunderland, "	7740	"	39	21.3	3.05	5.13	.075
69	Millers	Erving, "	372	Vernon, Vt.	8	17.1	2.26	4.58	.116
79	Ware	Gibbs Crossing, "	201	Springfield, Mass.	8	14.1	1.75	3.99	.155
80	Swift	West Ware, "	186	"	10	12.0	1.70	4.19	.178
86	Westfield	Westfield, "	496	"	13	85.6	4.28	5.76	.075
106	Housatonic	Falls Village, Conn.	618	"	9	18.9	2.96	5.51	.166
Average									0.16

A study of the rainfall-intensity graphs shows a sharp line of demarcation in the characteristics of the rain produced by these high-pressure areas. This line follows the Connecticut River closely. Throughout New England east of this line the rain lasted 12 to 18 hours, an average of 15 hours, and the average intensity at different stations ranged from about 0.1 inch to 0.28 inch per hour and the maximum hourly intensities ranged from 0.23 to 1.42 inch. West of the Connecticut River the rain lasted generally 33 to 43 hours, an average of about 36 hours. Average intensities at different stations ranged from 0.1 to 0.2 inch and the maximum intensities from 0.27 to 0.62 inch. The western cold front involved in this storm therefore produced a rain of more than twice as great a duration but of lower intensity than the eastern cold front. These facts are clearly brought out by Table 1, showing the storm-duration and average intensities at different recording gage-stations in the two regions. This storm produced a full-area flood on all the drainage-basins listed in Table 5.

Preceding the storm of November 2-5 there were light rains November 2 and October 28 and a period of four or five days of moderate to heavy rain throughout the entire region October 17 to 21. Owing to the low evaporation, the soil was well moistened and rain-packed. The storm occurred outside the season of earthworm- and insect-activity and the infiltration-capacity was at or close to the minimum for unfrozen ground. The drainage-basins ranged from high rocky mountainous areas, as in the upper Connecticut Valley, to extremely sandy areas, such as that of the Quinebaug River, and the infiltration-capacities given in Table 5 show corresponding variations. Those for the Connecticut River are particularly well determined because of the large number of rainfall-stations available. The values determined for different stations in the Connecticut Drainage-Basin are consistent, ranging from 0.05 inch per hour in the headwaters at South Newbury, Vermont, to 0.075 inch per hour at Sunderland, Massachusetts. The computed infiltration-capacities for the more generally sandy and somewhat less mountainous basins in Maine are higher, as would be expected. They are also less uniform but this may be in part due to paucity of rainfall-records. The computed values of infiltration-capacity on different areas are distributed as follows:

Less than 0.1 inch per hour,	11 areas
0.1 to 0.2 inch per hour,	10 areas
0.2 to 0.3 inch per hour,	2 areas
0.3 to 0.4 inch per hour,	2 areas
0.4 to 0.5 inch per hour,	1 area
0.5 to 0.6 inch per hour,	1 area

The average for all the areas is 0.16 inch per hour.

Infiltration-capacities from stream-rises described in Water-Supply Paper 772--Table 6 contains the results of determinations of the infiltration-capacity f for several drainage-basins in the eastern-central states. Runoff and other data used in these determinations have been derived from United States Geological Survey Water-Supply Paper 772. Some of these cases represent partial-area rises and the portion of the drainage-basin which produced surface-runoff is indicated in the Table. In such cases the infiltration-capacity f is computed relative to the fraction of the area which produced surface-runoff. In case of partial-area stream-rises, Table 6 shows the part of the drainage-basin which produced runoff in each instance. Some of the difference of infiltration-capacity f for different storms on the same area is due to differences in the part of the drainage-basin for which f was determined.

Discussion of results--Figure 9 shows the locations of drainage-basins for which infiltration-capacities are given in Tables 5 and 6. Omitting smaller basins included in larger ones, the total area for which infiltration-capacity has been determined is:

New England flood	20,363 square miles
Eastern-central areas	26,600 square miles
Total	46,963 square miles

Rainfall- and runoff-data for stream-rises suitable for determination of infiltration-capacity are available for nearly all drainage-basins in eastern-central United States and it is merely a matter of labor to extend the computation to cover the entire eastern part of the United States. In view of the now well-recognized fact that infiltration-capacity is a factor of primary importance in relation to surface-runoff, floods, and soil erosion, it is urged that computations be carried out and the results published for as many drainage-areas as possible. For reasons subsequently given it is desirable that a considerable part--preferably a dozen--determinations of infiltration-capacity should be made for each area at different times throughout the course of the year. On a given area, with the exception of highly impervious or highly

TABLE 6 - AVERAGE INFILTRATION ~ CENTRAL AND EASTERN DRAINAGE-BASINS

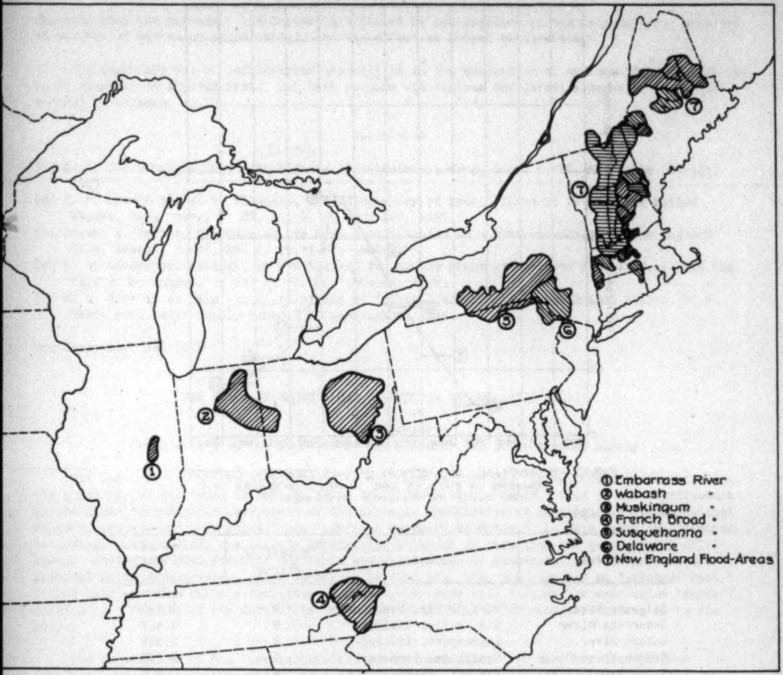
No.	Location Stream	Date	Drainage Area Sq.Mi.	Base Rainfall-Intensity Station	No. of rainfall stations used	Crest Discharge on whole area c.s.m.	Surface runoff on whole area inches	Effective Area	Runoff on Effective area inches	Mean rainfall on Effective area inches	Infiltr-Capacity on Effective area i.p.h.	Days since last wetting of soil (a)
(1)	(2)(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	Port Jervis N.Y.	Oct.30,1917	3070	Scranton and Binghamton	8	29.6	1.34	100%	1.34	2.27	0.055	1 L to M
2	Delaware	Oct.7,1918	"	"	7	5.15	0.28	"	0.28	0.97	0.11	4-7 L to M
3	"	June 3,1922	"	"	8	12.70	0.80	"	0.80	2.23	0.072	6 L to M
4	"	Apr.30,1923	"	"	9	8.8	0.56	"	0.56	1.54	0.070	8 L
5	"	Sept.30,1924	"	"	8	31.0	2.01	"	2.01	4.79	0.11	8 L
6	"	Oct.7,1926	"	"	8	4.4	0.29	78%-upper	0.41	1.95	0.235	5-9 L
7	"	Oct.5,1927	"	"	8	5.4	0.31	100%	0.31	2.38	0.395	16 L to M
8	"	Oct.13,1927	"	"	9	7.65	0.50	"	0.50	1.65	0.275	5 L, 9 H
9	"	Sept.4,1933	"	"	8	7.7	0.52	"	0.52	1.93	0.14	8-12 H
											0.162	
10	Ste. Marie, Ill.	June 25,1918	1540	Urbana	7	3.0	0.26	100%	0.26	2.38	0.57	5 L to M
11	Embarrass	May 12,1920	"	"	7	3.9	0.58	"	0.58	2.28	0.23	6 L to H, 8 L to M
12	"	Sept.15,1920	"	"	7	0.45	0.04	"	0.04	1.25	0.57	4-5 L to M
											0.457	
13	Logansport, Ind.	July 4,1925	3830	Ft. Wayne	14	0.79	0.07	20%-Lower Center	0.34	1.62	0.400	10-15 L to H
14	Wabash	Sept.27,1925	"	"	14	1.02	0.10	100%	0.10	1.47	0.355	7-9 L to H
15	"	Aug.3,1929	"	"	14	1.72	0.15	19%-Upper Center	0.80	3.70	0.495	10-12 L to H
16	"	Aug.14,1929	"	"	14	2.14	0.25	52%- center	0.48	2.22	1.24	5 L to M
17	"	June 29,1931	"	"	14	0.52	0.05	25%-upper	0.20	1.53	1.08	8-10 L to H
18	"	Oct.4,1932	"	"	14	0.55	0.05	31%-center	0.16	1.61	0.296	6-8 L to H
											0.643	
19	Dandridge, Tenn.	Aug.3,1921	4450	Asheville	12	8.53	0.57	100%	0.57	1.25	0.127	3 L, 6 L to M
20	French Broad	Apr.6,1922	"	"	13	4.27	0.26	54%-upper	0.49	1.19	0.116	5-9 L to H
21	"	Apr.18,1924	"	"	14	5.28	0.50	100%	0.50	1.25	0.045	3 L to H
22	"	Oct.12,1927	"	"	14	1.73	0.13	37%-upper	0.37	2.28	0.300	3-4 L to H
23	"	Apr.27,1928	"	"	14	4.95	0.45	100%	0.45	1.28	0.075	4-7 L to H
24	"	Apr.22,1931	"	"	13	5.97	0.49	"	0.49	1.57	0.18	4 L, 11 L to H
25	"	Sept.3,1931	"	"	13	3.95	0.27	"	0.27	1.26	0.18	4 L, 6 L to H
26	"	May 1,1932	"	"	13	6.51	0.56	"	0.56	1.83	0.255	7 L, 11 L
											0.160	
27	Towanda, Pa.	Oct.6,1918	7770	Binghamton	23	3.73	0.21	55%-Lower	0.39	1.00	0.16	3 L to H
28	Susquehanna	July 15,1921	"	"	20	1.17	0.07	26%-N.central	0.27	1.69	0.53	5 L to H
29	"	Sept.30,1924	"	"	23	16.71	1.50	100%	1.50	3.96	0.10	9 L to H
30	"	Oct.2,1929	"	"	19	3.60	0.29	"	0.29	2.81	0.33	15 L to H
31	"	June 10,1930	"	"	20	1.16	0.09	54%-Lower	0.17	1.36	0.27	12 L
32	"	Oct.6,1932	"	"	21	7.08	0.71	78%-N.Central	0.90	4.36	0.23	9 L to H
											0.270	
33	Dresden, Ohio	June 4,1927	5980	Columbus	14	4.00	0.44	100%	0.44	1.39	0.23	5 L to H
34	Muskingum	June 8,1929	"	"	15	0.87	0.05	42%-Lower	0.14	0.70	0.172	10 L to H
35	"	Aug.23,1929	"	"	15	0.52	0.05	27%-Lower	0.18	1.39	0.77	4 L to M
36	"	Aug.17,1932	"	Akron	16	0.45	0.05	26%-Upper	0.19	2.20	0.98	6 L
37	"	July 2,1933	"	"	16	0.90	0.08	44%-center	0.17	1.85	0.75	7 L to H
											0.580	

(a): L = Light rain ~0.0 to 0.5 inches
M = Medium " -0.5 - 1.0 "
H = Heavy " - > 1.0 inches

sandy areas, there is usually a considerable range between the minimum and maximum values of infiltration-capacity. It is therefore desirable that enough determinations be made for each area to show the minimum, maximum, and seasonal variations.

The data given in Table 5 for the New England flood relate to the same storm on different areas and the antecedent conditions were nearly the same.

A column has been added to Table 6 showing the last previous wetting of the soil on the drainage-areas in the eastern-central states. A study of this Table shows that other factors besides the time elapsed since the last rain must necessarily be taken into account in order to understand variations of infiltration-capacity in different storms on the same area. In general,



IG.9-LOCATION OF DRAINAGE-BASINS FOR WHICH INFILTRATION-CAPACITIES HAVE BEEN DETERMINED

the greater the time elapsed from the last wetting of the soil, the greater the infiltration-capacity. This is true, for example, in case of the stream-rises listed on Susquehanna River in Table 6. In case of Muskingum River, infiltration-capacities for midsummer conditions ranging from 0.125 to 0.98 inch per hour were obtained when the soil was relatively dry in all cases. The highest value is for the August 17, 1932, flood, at the end of a long dry period. For Delaware River, Table 6 shows five infiltration-capacities in October floods. The highest is for October 5, 1927, at the end of a long dry period. The lowest two occurred when the soil had been moderately wetted by recent rains.

In some cases it is necessary to go back beyond the last antecedent rain to interpret the result. Observations at the author's laboratory have shown that on sodded loam-soils, earthworms go down and remain at considerable depths during long dry periods. Earthworm- and insect-perforations may become closed by light rains, cultivation, and other causes, giving a very low infiltration-capacity when the first heavy storm occurs after a long dry spell, especially if there have been light antecedent rains which wetted the soil-surface but did not penetrate to great depth. After the soil has once been wetted to a sufficient depth, earthworm- and insect-perforations again appear at the surface. The author has counted as many as a hundred earthworm-perforations per square foot in a sodded soil late in the fall under these conditions. If then a heavy rain occurs, the infiltration-capacity may be abnormally high.

Comparing the different areas listed in Table 6, the following averages are obtained:

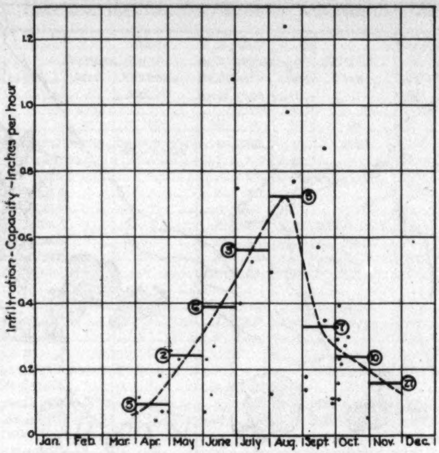


FIG. 10 — SEASONAL VARIATION OF INFILTRATION-CAPACITY
NUMBERS IN CIRCLES ARE NUMBER OF VALUES OF f
INCLUDED IN MONTHLY AVERAGE

Stream	Location	Number of storms	Average infiltration-capacity
			in/hour
Delaware River	Port Jervis, New York	9	0.162
Embarrass River	Ste. Marie, Illinois	3	0.457
Wabash River	Logansport, Indiana	6	0.643
French Broad River	Dandridge, Tennessee	9	0.160
Susquehanna River	Towanda, Pennsylvania	6	0.270
Muskingum River	Dresden, Ohio	5	0.580

It will be noted that the highest average values are those obtained for the Embarrass, Wabash, and Muskingum rivers, the drainage-basins of which are relatively flat, with permeable, cultivated soils, partly of glacial origin. Lower values were obtained for the Delaware, Susquehanna, and French Broad rivers. The upper Delaware and French Broad rivers are rocky, mountainous areas, uncultivated, and mostly forest-covered. The upper Susquehanna is mixed mountainous and agricultural land.

Table 5 shows a similar result with reference to the New England flood. The precipitous, rocky, mountainous, and forest-covered areas, such as the upper Connecticut Drainage-Basin, show generally lower infiltration-capacities than the flatter agricultural areas.

All of the infiltration-capacities given in Tables 5 and 6 have been averaged by months and the individual values and averages plotted, as shown on Figure 10. The average line shows a marked seasonal cycle of infiltration-capacity. The average curve is in good agreement with that obtained by the author showing seasonal variation of infiltration-capacity on Ralston Creek Drainage-Basin, Iowa (R. E. Horton, The role of infiltration in the hydrologic cycle, Trans. Amer. Geophys. Union, 1933, p. 482).

Figure 10 and data from laboratory and runoff-plat experiments and other areas indicate that during the midsummer months the infiltration-capacity is likely to be either close to the minimum or close to the maximum for the given area. Intermediate values occur, but less frequently than the maximum and minimum values. The minimum infiltration-capacity is a more definite quantity than the maximum. The latter is affected by sun-checking of the soil-surface, presence or absence of earthworm-perforations, and the effect of recent cultivation.

One important use of infiltration-capacity is in the estimation of maximum flood-intensities to be expected on a given area. For this purpose the minimum infiltration-capacity should in general be assumed.

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Voorheesville, New York

THE VALUE OF GEOPHYSICAL METHODS IN GROUND-WATER STUDIES

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Two meanings are unfortunately given to the term geophysics. In the broad sense, based on the etymology of the term, geophysics means the physics of the Earth. This is its significance in the names "Geophysical Laboratory of the Carnegie Institution of Washington," "International Union of Geodesy and Geophysics," and "American Geophysical Union." In this sense the sciences of geology and hydrology are largely geophysics, although in part they are geochemistry or biology. Geologists and hydraulic engineers who are elected to membership in the American Geophysical Union are, however, often surprised to find that they are regarded as "geophysicists." I hope that when the Union establishes a journal, its name will include the expression "Earth physics" or "Physics of the Earth," in order that there will be no misunderstanding as to its scope.

The popular use of the term geophysics is very restricted. It does not even include nearly all the instrumental methods of investigating the physics of the Earth. Thus, most of the instrumental methods developed for ground-water investigations are not commonly regarded as geophysical methods although they are based strictly on physics. Instruments used in applying these methods are water-level and pressure recorders, current-meters, and other devices for measuring the discharge of springs and wells, deep-well current-meters, salinity-apparatus and samplers, laboratory-apparatus for determining mechanical composition, porosity, moisture-equivalent, and permeability, instruments used in tests of underflow and permeability by the Slichter, Thiem, Theis, and dye methods, leveling and measuring equipment used in making contour-maps of the water-table or the piezometric surfaces of confined aquifers, lysimeters and boring, measuring, weighing, and drying equipment used in recharge-studies, and tanks and accessory apparatus used in determining specific yield and ground-water discharge by evaporation and transpiration. None of these is ordinarily considered as a "geophysical instrument," except that the Slichter apparatus and the deep-well salinity-apparatus have been partially adopted under that term. "Geophysical instruments," as popularly understood, are essentially those used in determining gravimetric and magnetic variations, electric conductivity, and artificial seismic effects in the Earth.

The automatic water-stage recorders are among the most valuable instruments of precision used in the study of ground-water. They are comparable to the seismic instruments in that they record natural variations of pressure-effects within the Earth and also artificial variations--produced not by explosions but by pumping or artesian flow from wells, often at considerable distances from the recording instrument. Indeed, water-stage recorders of a certain type have been adopted by the seismologists for recording pressure-effects of natural earthquakes, whereas water-stage recorders of various types are used by hydrologists, chiefly to record pressure-effects produced by several other agencies, both natural and artificial. It may be predicted that water-stage recorders will eventually come to have greater value in the study of the physics of the Earth, exclusive of hydrology, than is now understood, especially in studying the elastic properties of the rock-formations.

Geophysical methods, in the restricted sense, will undoubtedly prove of value in the study of ground-water, and the time is ripe for thorough and critical investigation of their possibilities. Their principal use at present appears to be along the line of prospecting, in extending the information derived from test-drilling and in making the drilling, whether for testing or for development, more effective. However, it appears almost certain that eventually these methods will prove to have substantial value in technical investigation and original research in hydrology. For example, the principal achievement thus far of the geophysical work in the Hawaiian Islands appears to be the verification and definition, by the electric resistivity-method, of the law of Badon Ghyben and Herzberg, relating to the balance between fresh and salt water, for the terrains of volcanic islands.

Geologic work has depended chiefly on the device of studying natural exposures of rock-formations and artificial exposures made in mining, well-digging and drilling, grading for railroads and highways, and excavation for other purposes. From the observations made at such random exposures, data are obtained from which the stratigraphy and structure of the rocks at intervening points and at greater depths are more or less accurately determined. Most of the natural exposures and many of the artificial exposures, however, are above the water-table and therefore do not have the decisive value for studying the occurrence, quantity, head, and quality of the ground-water that they do for studying the stratigraphy and structure. Information in regard to ground-water must be obtained largely from wells and other excavations that extend below the water-table, and hence our ground-water work has often been severely handicapped by lack of adequate well-data. In the past the funds available have generally not been sufficient to permit test-drilling, but with the greatly increased appreciation of the value of ground-water and of ground-water investigation, the sinking of test-wells of some sort is now a part of the program of most of the ground-water investigations made by the United States Geological Survey and the State and other governmental organizations with which the Survey cooperates. Thus, test-drilling or boring of some sort has been done in connection with the ground-water investigations on Long Island and in Croton Valley, New York; in the Atlantic City and Runyan areas and the shallow-water areas in New Jersey; in the basin of Difficult Run, Virginia; in the Elizabeth City area and in Robeson County, North Carolina; in extensive forested areas in Michigan; in the State-wide program in Nebraska; in the El Paso, Houston, and other areas in Texas and in connection with an extensive Works Progress Administration program in that State; in the San Luis Valley, Colorado, and the Middle Rio Grande Valley, New Mexico; in the Escalante and Ogden valleys and the vicinity of Salt Lake City, Utah; in the Mokelumne area, California; and in several localities in Hawaii. The deeper test-wells are generally drilled by contract, but for several projects we now have light drilling-rigs, which may be regarded with some poetic license as lengthened geologic picks. Geophysical methods are, in a sense, an extension along the same line. They extend the information obtainable from test-drilling. Their value will depend largely on their cost as compared with the cost of drilling and the precision of the data that they yield as compared with those derived from drilling.

Both the seismic and magnetic methods will doubtless prove valuable in ground-water work under certain conditions, but the most promising is the electric resistivity-method, which depends largely on the electric conductivity of the ground-water itself, and therefore comes closer than the other methods to giving direct hydrologic information. It was early recognized that a promising application of the resistivity-method is in locating salt water, for it is well known that salt water is much more conductive than ordinary ground-water. Thus, salt water has been rather definitely recognized in both the Hawaiian and the El Paso investigations, as is explained in the papers on this program by J. H. Swartz, and by A. N. Sayre and E. L. Stephenson. The method is not sufficiently exact to detect moderate differences in the mineralization of the water, and it therefore affords no substitute for analyses in the laboratory or even for field-tests of the mineral-content of the water except to a very restricted extent.

It was also recognized early in the development of the resistivity-method that earth-materials generally have greater electric conductivity when they are saturated than when they are relatively dry, and that therefore in many places the depth to the water-table can be determined approximately by this method. However, this determination is not sufficiently precise to be of much value. Moreover, the information that a formation is saturated is not of much value unless there is also information as to the capacity of the material to yield its water. The most important discovery in regard to the use of the electric resistivity-method in prospecting for ground-water was that to a considerable extent the coarse and clean materials, such as sand and gravel, offer higher resistance when saturated than do the saturated fine-grained materials such as silt and clay. The method has already been widely used, apparently with good results, in finding beds of water-bearing sand and gravel in valley-fill and glacial drift, especially where they occur within 100 or 200 feet of the surface. It is highly desirable that critical studies should be made of the exact relations between the electric conductivity and the water-bearing properties of the different earth-materials. For these studies it is necessary to drill test-wells in the areas explored by the resistivity-method, to get accurate logs and good samples from these wells, and to test the samples in the laboratory for mechanical composition, porosity, moisture-equivalent, and permeability. There should also be laboratory-research to determine the exact relations between the texture and the conductivity and causes of these relations.

It should be pointed out, however, that the information obtained from even the resistivity-method supplements that obtained from test-wells in only certain respects. Wells are still needed to determine the head of the water, the shape of the piezometric surfaces, and the direction of movement of the ground-water; the fluctuations of the water-levels in wells indicating depletion or recharge; the permeability and specific yield of the water-bearing beds; and the chemical composition of the water.

Valuable work has been done by a considerable number of investigators on the use of geophysical methods in ground-water investigations--notably by the Illinois Geological Survey, as reported by L. E. Workman and M. M. Leighton in a paper printed elsewhere in these Transactions. This work is summarized and critically analyzed and evaluated in the paper by C. A. Heiland, which is published in the Transactions. The Ground-Water Division of the United States Geological Survey is at present taking part in four investigations that involve the testing of geophysical methods--the El Paso and Hawaiian projects, in cooperation with F. W. Lee, the Chief of the geophysical unit recently transferred from the Bureau of Mines to the Geological Survey; the western damsite-investigations of the Conservation Branch of the Geological Survey under the direction of B. E. Jones, whose paper is printed in these Transactions; and the geophysical work, largely salt-water location and migration, in New Jersey, in cooperation with the State Water Policy Commission. If these four projects are carried through effectively, they ought to throw considerable light on the function of geophysical methods in ground-water work.

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RESISTIVITY-STUDIES OF SOME SALT-WATER BOUNDARIES IN THE HAWAIIAN ISLANDS

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Introduction--In the course of a systematic survey of the ground-water resources of the Hawaiian Islands which is being made under the direction of H. T. Stearns of the United States Geological Survey in cooperation with the Territorial Government of Hawaii, it was found desirable to test the utility of geophysical methods in the solution of certain Hawaiian water-supply problems. A cooperative geophysical survey for this purpose was undertaken by the Geophysical Section, then with the Bureau of Mines but later transferred to the Geological Survey, during the course of which a series of resistivity-studies of certain salt-water boundaries was begun. Since the location of such boundaries is of considerable importance in many areas it has been thougnt worth while to present the results which have thus far been obtained.

The problem--The growth of sugar-cane requires very large volumes of water. Because of the steep stream-gradients and the high permeability of the underlying lava-rocks it is not feasible to impound water in reservoirs to supply these demands. It hence becomes necessary to resort to ground-water for the development of adequate water-supplies.

Two types of ground-water are available for development, namely, (1) perched ground-water and (2) basal ground-water. Since the perched ground-water does not involve salt-water boundaries, it will not be further considered in this discussion.

Basal ground-water--Basal ground-water is formed by the downward percolation of rain-water which finally comes to rest on the surface of the sea-water that fills the porous lavas at greater depths throughout the Island. There it floats in general on the salt water as a fresh-water lens, the zone of mixture between the two being relatively narrow. Figure 1 gives a cross-section through a typical Hawaiian island, the black zone representing the fresh-water lens as determined by resistivity-measurements.

The flotation of such fresh-water lenses on bodies of salt water has long been recognized

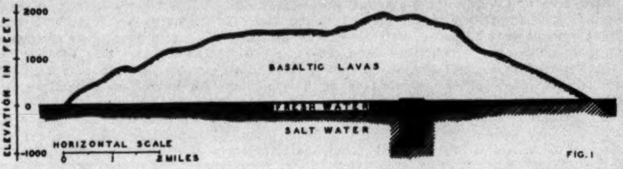

FIG. 1

in the literature [see 1 of references at end of paper], where it is usually referred to as the Badon Ghyben or Herzberg principle. It depends on the buoyancy-effects produced by the difference in density of fresh and salt water.

According to Stearns [2], the effective specific gravity of sea-water off Oahu is 1.024 for temperatures between 50° and 60° F. Since fresh water in the same temperature-range has an effective specific gravity of 0.999 [3], it follows that one foot of salt water will counterbalance 1.025 feet of fresh water at the temperatures normally encountered in such fresh-water lenses. Hence for every foot of fresh water below sea-level there will be 0.025 feet of fresh water above sea-level, and conversely, for every foot of fresh water above sea-level there must be 40 feet of fresh water below sea-level. (This relationship will, of course, hold true only where the ratio of the specific gravities of fresh and salt water is 1/1.025. Any change in the values of the specific gravities, from whatsoever cause, will of course produce a corresponding change in the ratio of the thickness of fresh water above sea-level to that of fresh water below sea-level.)

From the standpoint of water-development it is of vital importance to know the thickness of this fresh-water lens. Due to the density-differences noted above the salt-water surface will rise approximately 40 feet for every foot of draw-down of the water-table in pumping. If the lens is thin, water of high salinity is likely to be obtained.

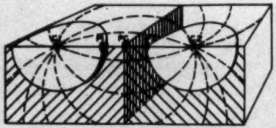

FIG. 2

This is such a serious factor that a special type of well has been developed in the Hawaiian Islands, a sort of water "mine," to which H. T. Stearns [4] has applied the name "Maui-type well." A shaft is put down to or slightly below the basal water-table and skimming tunnels are run out laterally for several hundred feet to collect the volume of water needed without seriously lowering the water-table [5].

The resistivity-survey

Resistivity-method used--All resistivity-measurements during this survey were made by the Lee partitioning method. In this method, as shown in Figure 2, an electric current is passed into the ground by means of two iron stakes driven into its surface. Due to this current flow a voltage is set up between any two points on the ground-surface, for example, P_1 and P_c in the Figure. This voltage may be measured by placing suitable potential-electrodes at P_1 and P_c and determining the potential difference between them by means of a potentiometer or other potential-measuring device.

The voltage between the two potential electrodes depends on three things: (1) The current, I, flowing through the ground; (2) the relative spacing of all the electrodes, both current and potential; and (3) the electrical resistivities of the materials underground. Since the current

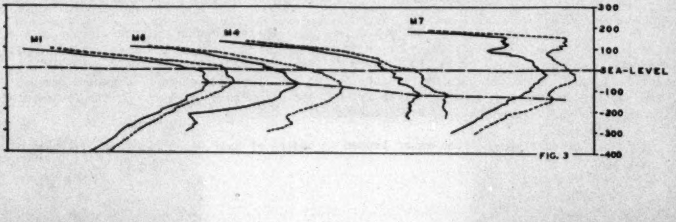

FIG. 3

and electrode-spacings are at all times carefully controlled, any anomalies in the measured voltages must be due to the factor which is not controlled, namely, the resistivities of the materials underground. It has been found, purely as a matter of field-experience, that the material chiefly responsible for such an anomaly is that lying at a depth, a, which, in the partitioning method, is equal to one-third the distance between the current-stakes for the particular electrode-spacing at which the anomaly was observed.

In the partitioning method the potential electrode P_c is normally placed half way between the two current-stakes C_1 and C_2. The two lateral potential-electrodes P_1 and P_2 are then placed on either side of P_c at a point one-third of the distance from P_c to C_1 and C_2, respectively. These dimensional relationships are maintained unchanged throughout the measurements, regardless of the particular numerical values of the electrode-separations, so that we always have $C_1P_1 = C_2P_2 = P_1P_2 = 2\ P_1P_c = 2\ P_2P_c = 1/3\ C_1C_2 = a$.

Since a is the effective depth of measurement, it follows that the depth can be changed merely by changing the numerical value of a. By thus changing the value of a, the changing resistivities due to the materials lying at different depths may be determined. The apparent resistivity of the material lying between the median plane through P_c and the hemispheroidal equipotential bowl which passes through P_1 (or P_2) and which surrounds, slightly eccentrically, the current-stake C_1 (or C_2) as shown in Figure 2, may be calculated from the formula

$$\rho = 4\pi a(E/I)$$

where ρ is the apparent resistivity in ohm-centimeters, a is the distance C_1P_1 (which equals C_2P_2 and is $1/3\ C_1C_2$) expressed in centimeters, E is the voltage between P_1 (or P_2) and P_c in millivolts, and I is the current in milliamperes flowing through the circuit.

The different values of ρ are then usually plotted as ordinates against the corresponding depths as abscissae, as shown in Figures 4 to 9. As there seen, two curves are always obtained by the partitioning method, one each for the materials lying on either side of the median or partitioning plane through the central electrode.

In these curves an upbreak (a counter-clockwise rotation of the curve-slope) usually occurs where a higher resistivity is encountered as depth is increased, a down-break (a clockwise rotation of the curve-slope) where a lower resistivity is met.

Results of the resistivity-survey--Resistivity measurements were begun on the island of Maui, some 90 miles southeast of Honolulu. A series of resistivity-stations were run just south of the town of Spreckelsville. The resultant resistivity-curves are shown in Figure 3. On each of these curves a down-break was found, indicating a horizon of lower resistivity, a short distance below sea-level. As the traverse was extended inland away from the sea, this down-break was found to occur at increasing depths. Since the lava-flows rise in this direction, it is obvious that this resistivity-change is not stratigraphic in character, and the conclusion is reached that this resistivity down-break represents the top of salt water of approximate sea-water salinity filling the interstices of the underlying lava-rocks.

A similar down-break was found on all the curves run sufficiently below sea-level on both the islands of Maui and Lanai, as shown in the curves of Figures 3 to 9.

Corroborative evidence

Kahului Fair-Ground drill-hole--An opportunity was afforded to make a direct test of this conclusion through the courtesy of J. H. Foss, of the Maui Agricultural Company, and C. S. Childs, Director of the Alexander Settlement, Wailuku, with the cooperation of J. M. Heizer and Robert Hughes.

Maui County had decided to drill a shallow diamond-drill hole at the Kahului Fair-Grounds to determine the possibility of a water-supply for a proposed swimming pool. While preparations were being made for drilling, a careful resistivity-test was run as close to the drill-hole location as possible. The resultant resistivity-curves, given in Figure 4, show a down-break below sea-level, identical in character with those of the Spreckelsville-Pukulani Road traverse shown in Figure 3, at a depth of 140 ± 1 feet below the surface, or 135.2 ± 1.0 feet below sea-level. When this was discovered, a request was made that the drill-hole be carried down 150 feet instead of being stopped at 60 feet as originally planned. This request was cordially granted.

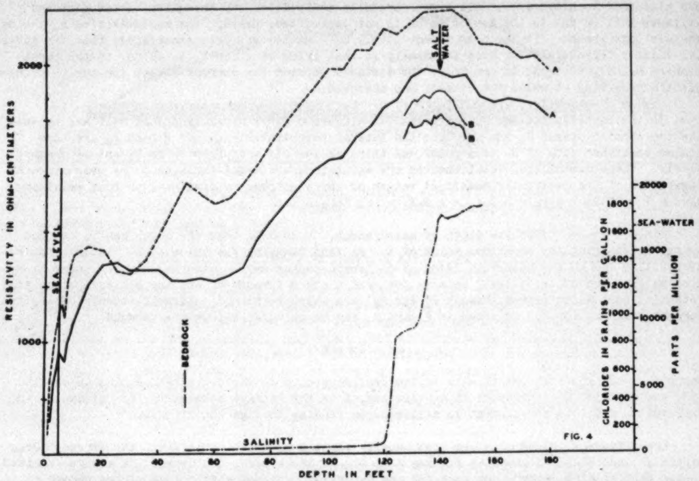

FIG. 4

After the completion of the drill-hole a series of samples were pumped from the well at one-foot intervals by Mr. Hughes, and each sample was analyzed for chloride-content in the laboratories of the Hawaiian Commercial and Sugar Company at Puunene. The resultant salinity-log of the well is plotted in Figure 4 below the resistivity-curves. As there shown, the salinity rose abruptly from water of low chloride-content at a depth of 119 feet to water of approximately sea-water salinity at a depth of 141 feet below the surface, a value from which the salinity at greater depths did not vary greatly. On the basis of this salinity-curve, the top of the salt water should be placed 141 feet below the surface, a depth of 134.4 feet below sea-level. This is in close agreement with the value 135.2 ± 1.0 feet obtained in the resistivity-measurements as noted above.

While in this particular case the difference between predicted and observed results is less than one foot, it is not anticipated that resistivity-determinations of the depth to salt water will in general be so close. There will always, of course, be a possible error equal to the depth-interval used in the measurements, and it usually will not be economical to employ the one-foot interval here utilized. Furthermore, there will be occasional locations where dense rocks may occupy the position which would otherwise be held by the top of salt water of sea-water salinity, thus preventing the registration of the salt-water resistivity-break until the resistivity-measurements reach a greater depth at which porous rocks saturated with sea-water are encountered. In addition, where pumpage is heavy the zone of mixture may become so broad as to render difficult the determination of the exact position of the salt-water down-break in the resistivity-curve. Since this study is still in a preliminary stage, there may

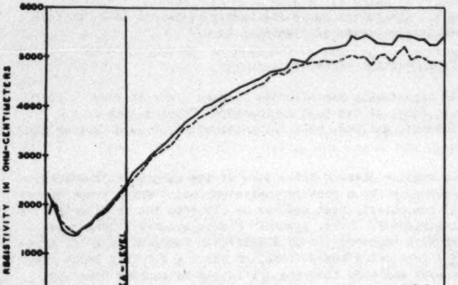

FIG. 5

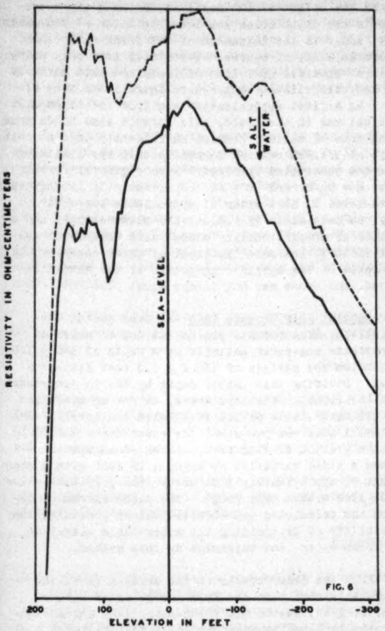

FIG. 6

be other factors not yet recognized or fully understood which may also affect the resistivity-determinations. With these limiting factors in mind, however, it is probably safe to expect, from the results here obtained, that wherever conditions are satisfactory, determinations of the depth to salt water of sea-water salinity may be made by resistivity-measurements with reasonable accuracy.

Width of the zone of mixture--It is interesting to observe the narrowness of the zone of mixture--only 22 feet at the Kahului Fair-Grounds' drill-hole. It is this abrupt transition from fresh water to sea water with the resultant rather sharp contrast between fresh-water and salt-water resistivities that makes feasible the use of resistivity-measurements for the determination of depths to salt water and that permits them a considerable sensitivity in making such determinations.

Where pumping occurs, the zone of mixture is considerably widened as was indicated by the resistivity-measurements made at Pump 7 of the Hawaiian Commercial and Sugar Company, Maui, which has a pumping capacity of 40,000,000 gallons per day. The rounding off of the resistivity-curve, shown in Figure 5, is in marked contrast to the sharp break due to salt water in the Kahului Fair-Grounds curve, shown in Figure 4.

Application of resistivity-measurements to the prediction of water-table elevations and basal fresh-water lens thickness--The possibility of determining the depth to water of sea-water salinity by resistivity-measurements immediately leads to the possibility of determining from this depth by calculation the elevation above sea-level of the basal water-table and the thickness of the fresh-water lens.

If the Badon Ghyben-Herzberg hypothesis is applicable in the Hawaiian Islands and the basal fresh-water lens is floating on sea-water, it follows, as discussed above, that the fresh-water lens must rise approximately 0.025 foot above sea-level for every foot of fresh water below sea-level. Hence, as a first approximation

$$h = D/40 \quad \text{and} \quad t = (h + D)$$

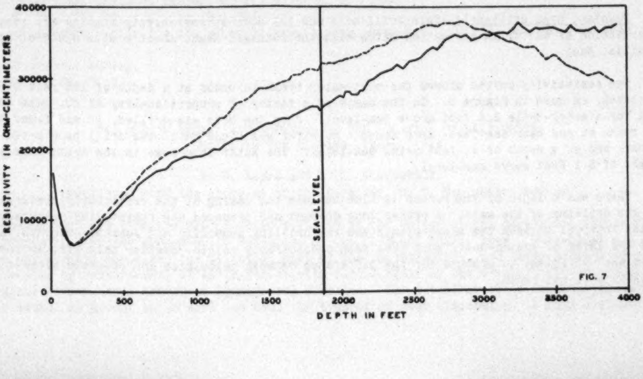

FIG. 7

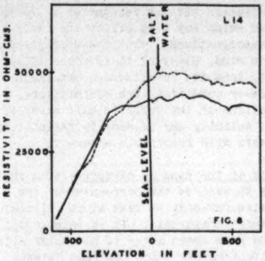

FIG. 8

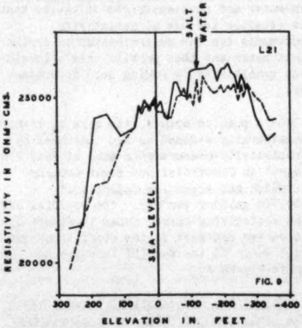

FIG. 9

where h is the height of the basal water-table above sea-level, D is the depth below sea-level to water of sea-water salinity, and t is the thickness of the fresh-water lens. (This formula will, of course, be strictly true only where the ratio of specific gravities of fresh and salt water is 1/1.025 and theoretically only where there is no zone of mixture. As a first approximation and from the standpoint of practical use in the field, this formula also holds true where the zone of mixture remains sufficiently thin so that the ratio of 1/1.025 remains correct within the limits of error of the quantities involved. A more general formula would be $h = D_r/n$ and $t = (h + D_r)$, where D_r is the depth below sea-level to salt water of approximate sea-water salinity, as determined by resistivity-measurements, and n is a factor of proportionality whose value depends on several factors, the most important of which, however, is the ratio of the specific gravities of the waters involved, and hence may not always equal 40.)

Kahului Fair-Grounds test--As seen above, the resistivity-measurements placed the top of water of approximate sea-water salinity at a depth of 140 ± 1.0 feet below the surface or 135.2 ± 1.0 feet below sea-level. Dividing this latter depth by 40, in accordance with the formula discussed above, we get an elevation for the water-table of 3.4 feet above sea-level. When the drill-hole was put down, the water-table was found at an elevation of 3.43 feet. Later measurements showed a tidal variation of about 0.18 foot with a mean height of approximately 3.34 feet. The predicted value hence lies within this range. The close agreement between the calculated and observed values indicates the feasibility of determining the water-table elevation and fresh-water lens thickness by this method.

From the measurements in the drill-hole of the water-table elevation and from the salinity-data of the depth to salt water, the ratio of the specific gravities of the fresh-water lens and the underlying salt water may be calculated. This ratio is found by dividing the total thickness t of the fresh-water lens by the depth D below sea-level to the top of salt water. As determined from the salinity-curve of Figure 4, D equals approximately 134.4 feet. The water-table ranges with the tide from about 3.25 to 3.43 feet above mean sea-level. The value of D, measured from mean sea-level, will also vary with the tide but in the reverse direction. Since the exact stage of the tide at which D was determined is not known, we may say, as a first approximation, that the value of t is probably about 137.8. From this we get $t/D = 137.8/134.4 = 1.0253$, which is in satisfactory agreement with the ratio 1.025 calculated from the measured specific gravities in the earlier part of this paper.

Pukulani Road drill-hole--This drill-hole was put down at resistivity-station M7, near the intersection of the Haiku Irrigation Ditch with the Pukulani Road, about a mile south of Spreckelsville, Maui.

The resistivity-curves showed the salt-water break to occur at a depth of 135 feet below sea-level, as seen in Figure 6. On the basis of a factor of proportionality of 40, this would call for a water-table 3.4 feet above sea-level. When the hole was drilled, it was found that the rocks at and near sea-level were dense. No water was found until the drill penetrated a clinker bed at a depth of 11 feet below sea-level. The water then rose in the drill-hole to a height of 5.1 feet above sea-level.

There was a lapse of five months in time between the making of the resistivity-measurements and the drilling of the well. A rather long drought had preceded the resistivity-measurements. In the interval between the measurements and the drilling unusually wet weather obtained, so that the level of ground-water must have been considerably raised. Whether this rise in the water-table was sufficient to account for the difference between calculated and observed water-table elevations is not known.

Lower Mauna Lei shaft, Lanai--An excellent test was obtained on the Island of Lanai during the sinking of the new Mauna Lei shaft in lower Mauna Lei Canyon. It was impossible to make resistivity-measurements at the site of the shaft because of pipe-lines buried at or near that point. However, it was found possible approximately to bracket the shaft between resistivity-stations L14 and L21 located on opposite sides of the shaft and each approximately three-quarters of a mile away from it. The resistivity-curves obtained at these two stations are shown in Figures 8 and 9.

At Station L14, to the northwest of the shaft, the resistivity-curve shows a depth to salt water of 60 feet below sea-level, as seen in Figure 8. Using the usual proportionality factor of 40, this gives a water-table only 1.5 feet above sea-level, suggesting probably undesirable salinity. The resistivity-curve for Station L21 of Figure 9 shows the salt water at a depth of 123 feet below sea-level. On the basis of a one to forty ratio this gives an elevation of 3.1 feet for the water-table. Interpolating, a value of 2.3 feet is obtained for the elevation of the water-table at the shaft. When the water-table was reached in the shaft, one month later, the water-table was found to lie at an elevation of 2.21 feet above sea-level, an agreement closer than had been anticipated from the locations of the stations and the electrical interferences involved.

As anticipated from the thin lens indicated by the resistivity-results, the water was found to have a rather high salinity, namely, 35 grains per gallon or 364 parts per million.

Conclusions

It would appear from these results that in the Hawaiian Islands it is feasible to determine the depths to salt water below sea-level by means of resistivity-measurements made with the partitioning method; also to test to what extent the Badon Ghyben-Herzberg principle is applicable and to ascertain the factors which produce variations from this principle.

Further drilling-tests are in progress and additional and more extensive resistivity-surveys are being planned. It is hoped that much added information will shortly be available as a result of these further investigations.

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U. S. Geological Survey,
Washington, D. C.

THE USE OF RESISTIVITY-METHODS IN THE LOCATION OF SALT-WATER BODIES IN THE EL PASO, TEXAS, AREA

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(Published with the approval of the Director, U. S. Geological Survey)

During 1935 and 1936 the Ground-Water Division of the United States Geological Survey made an investigation of the ground-water resources of the El Paso, Texas, Area. Geological and hydrological studies comprised the principal part of the investigation, and these studies were supplemented by measurements of earth-resistivity made largely by the Geophysical Section of the Geological Survey along traverses aggregating 51 miles. The extent to which resistivity-methods may be useful in ground-water work has been the subject of much discussion. A full evaluation

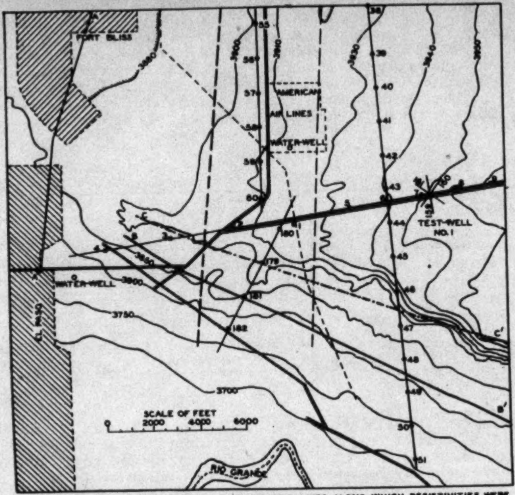

A
FORT BLISS
3880
3900
3910
3930
3940
3950
AMERICAN
AIR LINES
WATER-WELL
TEST-WELL
NO. 1
C
C'
B'
A'
WATER-WELL
3850
3800
3750
3700
EL PASO
SCALE OF FEET
0
2000
4000
6000
RIO GRANDE
35
38
39
40
41
42
43
44
45
46
47
48
49
50
51
55
56
57
58
59
60
179
180
181
182

FIG. 1—MAP OF AN AREA NEAR EL PASO SHOWING LINES ALONG WHICH RESISTIVITIES WERE MEASURED AND SALT-WATER BOUNDARIES AS DETERMINED FROM THESE MEASUREMENTS

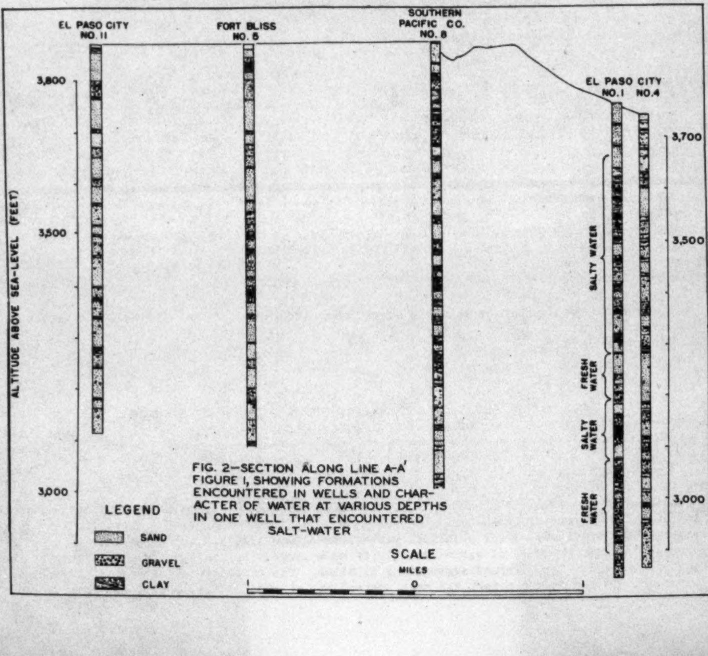

EL PASO CITY
NO. 11
FORT BLISS
NO. 5
SOUTHERN
PACIFIC CO.
NO. 8
EL PASO CITY
NO. 1
NO. 4
ALTITUDE ABOVE SEA-LEVEL (FEET)
3,800
3,500
3,000
3,700
3,500
3,000
SALTY WATER
FRESH WATER
SALTY WATER
FRESH WATER
LEGEND
SAND
GRAVEL
CLAY
SCALE
MILES
1
0
1

FIG. 2—SECTION ALONG LINE A-A' FIGURE 1, SHOWING FORMATIONS ENCOUNTERED IN WELLS AND CHARACTER OF WATER AT VARIOUS DEPTHS IN ONE WELL THAT ENCOUNTERED SALT-WATER

of the method can not be made at this time. However, the work in the El Paso Area indicates that the presence of faults and of underground bodies of salt water may be definitely determined by resistivity-measurements.

El Paso, as shown in Figure 1, is situated chiefly in the Rio Grande Valley at the west side of the Hueco Bolson. The Hueco Bolson is a nearly flat-bottomed basin, 60 miles long and 20 miles wide, that lies between sub-parallel north-south trending mountains. The Rio Grande has carved, in this nearly level surface, a steep-walled, flat-bottomed valley six to eight miles wide and about 300 feet deep. The escarpment between the valley and the bolson floor is so abrupt that from the valley the nearly level bolson-floor appears to be the edge of a broad upland and is therefore locally called "the Mesa." The Hueco Bolson, including the Rio Grande Valley, is underlain by 5000 feet or more of unconsolidated sands, gravels, and clays, the upper parts of which are illustrated in the section prepared in Figure 2. The sands and gravels, especially near the city, supply nearly all of the water used in the area, except water for irrigation.

The sands are more or less lenticular and no attempt has been made to correlate beds shown in Figure 2 although certain beds appear to extend across all of the section. The radical differences in the chemical character of the water in successive beds indicate that some of the clay-beds are sufficiently extensive to prevent vertical migration of water. Beneath the Mesa only fresh water is encountered in the beds of sand between the water-table, at a depth of about 200 feet, to the depth of at least 900 feet, the deepest beds from which water-samples were obtained. Beneath the valley, certain of the beds contain highly mineralized water, although there is wide variation in the mineralization from place to place. Near the eastern limits of El Paso wells encounter beds containing salt water from the water-table, at about 100 feet, to a depth of about 500 feet, fresh water from about 500 to 600 feet, salty water from 600 to 700 feet, and

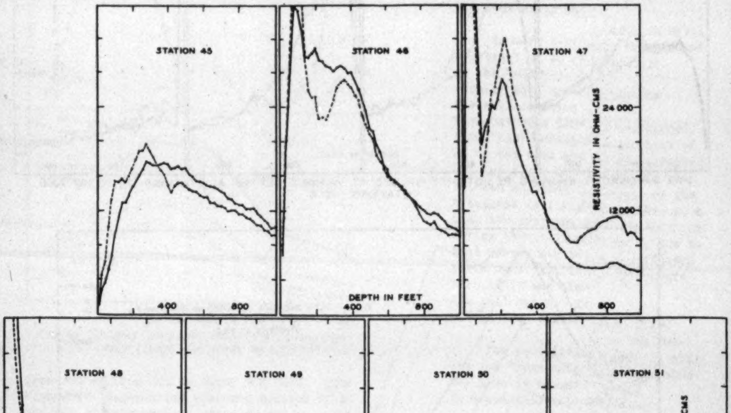


FIG. 3—GRAPHS SHOWING RESISTIVITY-VALUES AT VARIOUS DEPTHS AT STATIONS 45 TO 51

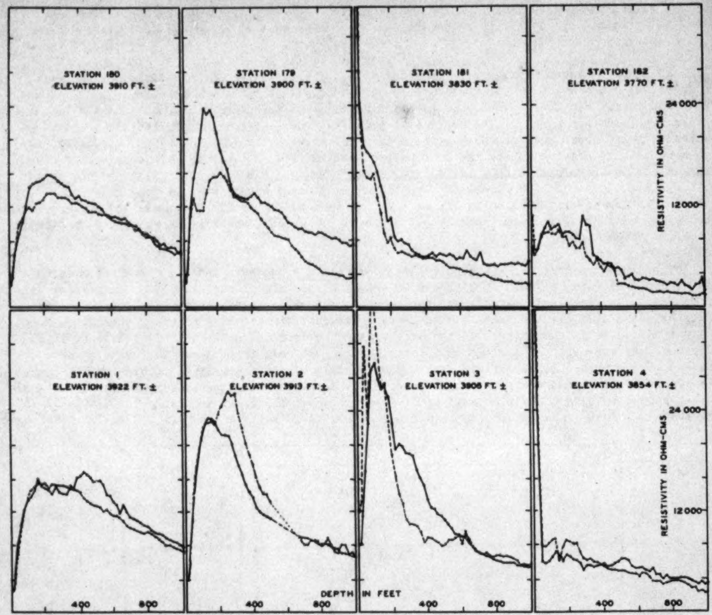


FIG. 4—GRAPHS SHOWING RESISTIVITY-VALUES AT VARIOUS DEPTHS AT STATIONS 179 TO 182 AND STATIONS 1 TO 4

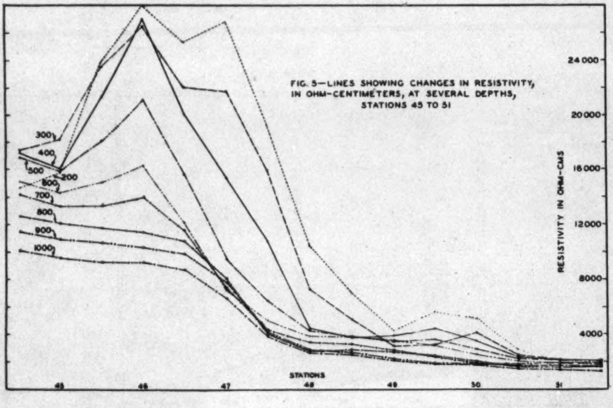


FIG. 5—LINES SHOWING CHANGES IN RESISTIVITY, IN OHM-CENTIMETERS, AT SEVERAL DEPTHS, STATIONS 45 TO 51

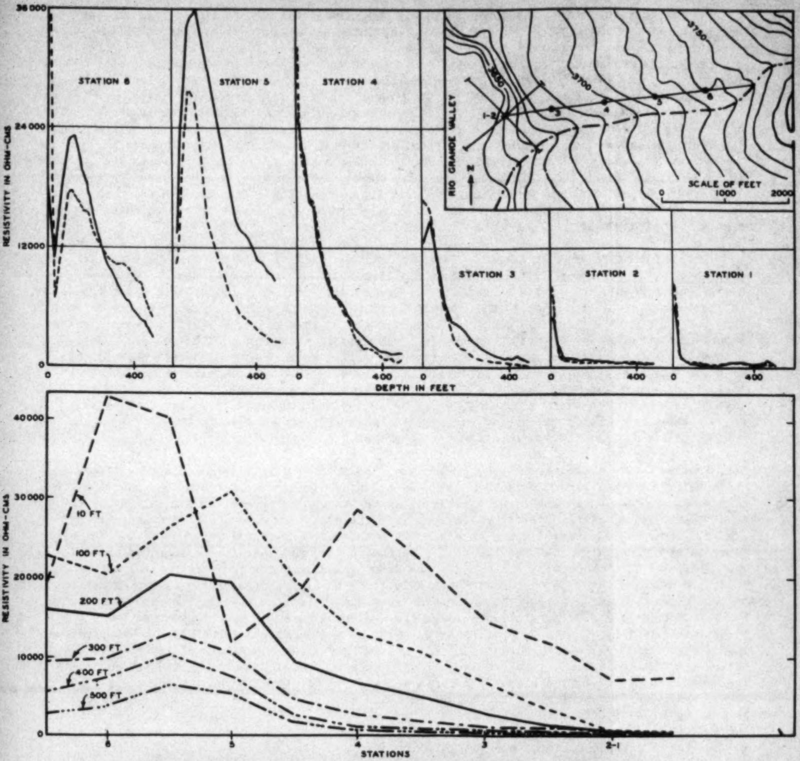


FIG. 6—GRAPHS SHOWING RESISTIVITY-VALUES AT VARIOUS DEPTHS, STATIONS 1 TO 6, NEAR CLINT, TEXAS, AND LINES SHOWING RESISTIVITY AT SEVERAL DEPTHS AT EACH OF THESE STATIONS

fresh water from 700 to about 900 feet. Below 900 feet salt water is encountered, as shown in Figure 2. Beneath the business section of El Paso, the highly mineralized water contains large amounts of calcium and magnesium and is excessively hard.

Since a large number of wells are drilled within the valley, the occurrence of the salt water, and particularly the location and character of the boundary between the salt-water area and the fresh-water area, has an important bearing upon ground-water withdrawals in the El Paso Valley. In order to effectively develop the ground-water supplies of the area in and near the valley and to minimize the danger of salt-water contamination, it is desirable to delimit the salt-water areas and to determine the nature of their boundaries.

For the purpose of locating the salt-water boundary, three vertical resistivity-traverses were run from the fresh-water area into the salt-water area. Figure 1 shows the locations of these traverses. Resistivity-stations were spaced 1500 feet apart on these lines and resistivity was measured to depths of 1000 feet. Figure 3 shows the resistivity-curves of stations along the longest of these traverses.

The resistivity-curve at Station 45 is typical of the curves obtained in this section of the Mesa. In approaching the valley, the near-surface values increase rapidly until the surface-resistivity is the highest resistivity measured at the Station. The resistivities at greater depths decline gradually and then at Station 47 begin to drop abruptly. From this point toward the center of the valley all resistivities decline to very low values and the curves become almost featureless. Figure 4 shows resistivity-curves for two other traverses, which show the same series of changes. Figure 5 is a horizontal resistivity-profile along the traverse indicated. The stations along the traverse are plotted as the abscissae. The resistivities at each 100-foot depth at a single station are plotted as the ordinates. This diagram shows more clearly the same sequence of changes shown by the vertical resistivity-curves. There is the increase in near-surface resistivity, followed by a sharp drop. The resistivity at the greater depths declines slowly at first and then abruptly. The drop, producing a terrace-like front in the curves, continues until at Station 48 the curves flatten out at a lower level, representing resistivities of approximately 2000 ohm-centimeters.

The significance of this series of changes in resistivity toward the valley is not yet fully understood. The low resistivities found at stations 49 to 51 are clearly due to the presence of highly saline water beneath the surface. The edge of the Area underlain by this water appears to lie between stations 48 and 49 and between 3 and 4 and 181 and 182, as shown by the solid line B-B' in Figure 1. The hydrologic evidence indicates that there is a belt between the fresh-water and salt-water areas that is underlain by moderately salty water. The sequence of resistivity-changes, repeated on three different traverses, would seem to indicate that in this belt the salinity increases as the valley is approached. The sharp increase in near-surface resistivities shown in Station 46 and in stations 179 and 2 may be the first indication of the edge of this belt. However, the increase may be due to the higher resistivity of sands and gravels encountered below the valley-rim near which these stations are situated. The edge of the moderately saline belt is indicated by the broken line C-C' (Fig. 1).

Another series of measurements was made near the town of Clint, Texas, about 19 miles southeast of El Paso. The town authorities had selected a well-site for the town near the foot of the valley-wall and requested a resistivity-survey to determine whether the well would encounter salt water. Two resistivity-stations at right-angles to each other were measured at the well-location (stations 1 and 2 in Fig. 6). Additional measurements were made at four stations along a line extending from the well-site toward the Mesa. As in the traverse near El Paso, they indicate decreasing salinity as the Mesa is approached. The traverse was not extended to the Mesa and the type of curve characteristic of this part of the Mesa was not determined, but the curve at Station 6 suggests that fresh water underlies the station. An abandoned well between stations 5 and 6 is reported to have yielded fresh water. The curves at stations 1 and 2 suggest that highly mineralized water here underlies the surface. Therefore, it was predicted that the proposed well would encounter highly mineralized water. A sample of water collected during the drilling was analyzed by the Water-Resources Laboratory of the United States Geological Survey and found to contain 18,268 parts per million of dissolved solids, of which 9350 parts were chloride. Because of the slight increase in resistivity at about 190 feet (see Station 1) it was also predicted that water of somewhat better quality would be encountered beneath the salt water. This prediction was also verified by the drilling, but the deeper water, although less highly mineralized, was not potable.

The resistivity-data give some information on the nature of contact between the salt water and the fresh water. Three conditions are possible: That the area is bounded by a fault; that the area is bounded by impermeable beds through lensing of the formations; or that the contact is a water-to-water contact.

The resistivity-tests show definitely that the salt-water area is not bounded by a fault. The resistivity-curves indicate a zone of mixing of salt and fresh water such as might be expected along a migratory contact. The hydrological and geological studies show that there is not an impermeable barrier between the water-bearing beds beneath the valley and those beneath the Mesa. While it is known that the bolson-deposits are somewhat lenticular, it is evident that at least a part of the beds are continuous from the valley-area to the Mesa area and that the contact is a water-to-water contact as illustrated in case three. There is indisputable evidence that the water in the Southern Pacific wells at the edge of the Mesa, near Fort Bliss, is now more highly mineralized than when the wells were drilled, indicating that salt water has migrated northward from the valley.

U. S. Geological Survey,
Washington, D. C.

RESULTS TO BE EXPECTED FROM RESISTIVITY-MEASUREMENTS

B. E. Jones

(Published with the approval of the Director, U. S. Geological Survey)

The work described in this paper was all done in connection with dam-site investigations and was not directly connected with hydrology. However, geophysics is coming to have a place in hydrologic investigations, and these results may throw some light on what can be accomplished by resistivity-measurements.

We have found that, for many questions not involving exact determinations of depth, resistivity-measurements give conclusive answers. Ordinarily a reliable answer can be expected to the question of the existence of a buried channel if the covering is composed of unconsolidated material with a resistivity differing from that of the rock. For example, topographic surveys were made at two alternative dam-sites on a river about four miles apart. Examination of the surface-geology indicated that a channel buried under glacial debris possibly existed at each site, but resistivity-measurements proved that such a channel existed at one site and not at the other. On the other hand, at another site the geologist suspected there might be an old channel on a steep side hill. Geophysical measurements showed a depth of overburden of 46 feet and showed that if a deeper channel exists it must be narrow; but they did not show positively that no such channel exists. Probably a careful survey with a large number of lines would have given a more definite answer, but the rough topography interfered with the resistivity-work, and time and money were not available for a detailed survey. After completion of the geophysical work, the geologist located some outcrops which led him to conclude that no old channel exists at this site. At two other dam-sites in Oregon resistivity-measurements showed that there were no buried channels.

At a dam-site in Montana the location of the best cross-section for a dam depended on whether a terrace was composed of rock, mantled with outwash, or whether it was a terrace composed of outwash material. Geophysical measurements showed that the terrace was of the latter type.

These are typical examples of questions that can be definitely answered by geophysics.

The question that arises most often at dam-sites, however, is the depth of the overburden. At first glance it would appear to be impossible to give any general figures on the accuracy of depth-determinations obtainable by resistivity-measurements because so many factors are involved. The accuracy obtainable in determinations of depth to rock depends, among other things, on the depth of overburden, on the contrast in resistivity between the rock and the overburden, on the surface-topography, and on the regularity of the bed-rock surface. The accuracy obtainable at a given site can be predicted to some extent from information regarding these points. Two sources of indeterminate errors are: First, the assumption that a given change in resistivity is due to rock when in reality it is due to a layer of material other than rock but which has a different resistivity from the layer above; and second, the failure to carry out the resistivity-measurements to a sufficient interval to permit a correct estimate of depth to rock.

The only way to take into consideration all sources of error is to consider those sites where resistivity-estimates have been followed by drilling. As this will limit us to two dam-sites for which such information is available but which are not representative, our results will not be conclusive. They will, however, indicate at least one error to be avoided and will show what accuracy was obtained at these sites.

The first site to be drilled after resistivity-measurements were obtained was on Nevada Creek in Montana. Four determinations of depth to rock were made by resistivity-methods at convenient points. These points were not on a line and not on the line where the drill-holes were put down, but they were within 600 feet or less of the drill-holes. A cross-section has been drawn as shown in Figure 1 and compared with the cross-section obtained by drilling. On the right bank a depth of 53 feet was obtained by resistivity-measurements. The actual depth is at least 39 feet and may be as much as 50 feet. At one point in the creek bottom the estimated depth, based on resistivity-measurements, was 27 feet, and at a second point in the bottom the estimated depth was 35 feet. The maximum depth obtained by drilling was 27 feet. At a point on the left abutment the depth to the hard bed-rock, a quartzite, was estimated at 85 to 100 feet, based on resistivity-measurements. A hole was drilled to a depth of 75 feet and passed through shale, gravel, and clay, but did not reach the quartzite. The results of the resistivity-measurements at this site are not accurate when compared with drilling, but they do give a rough idea of the depth to rock, from which the value of the dam-site can be judged. Resistivity-measurements at a site lower down the creek gave depths to bed-rock much greater than at this site, so even if we allow a large margin of error we are safe in assuming that this is the better site as regards depth of overburden.

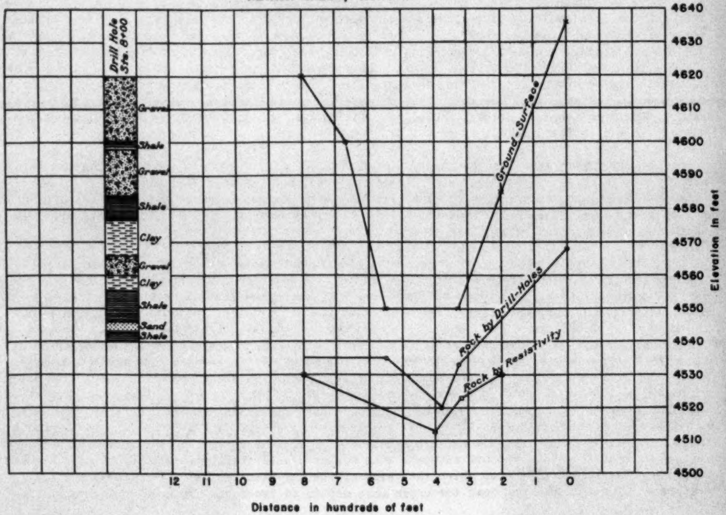
A second dam-site at which drilling followed resistivity-work is located on the Pine River in Colorado. At this site measurements were made during February and March with about two feet of snow on the ground and temperatures as low as 10° below zero.

The rock itself has a low resistivity and is covered by various layers of material deposited by glaciers and in lake-bottoms, so it was difficult to distinguish the rock from some of the layers of overburden. The stream was perched above the water-table. Two drill-holes had been put down. At a depth of 52 feet in one of these holes the log reported "sandstone, red bed-rock." Resistivity-measurements carried out to an interval of 200 feet at this hole gave a good curve that indicated changes of material at depths of 27 and 70 feet. Actually the depth to rock was in the neighborhood of 200 feet, and the change in resistivity at a depth of 70 feet was probably due to the presence of ground-water. The drillers mistook a cemented gravel for sandstone, and because of this mistake the first resistivity-measurements were not carried out to a sufficient interval to indicate bed-rock. At another drill-hole, which went to 83 feet without encountering rock, the resistivity-measurements gave a very poor curve for intervals over 80 feet, possibly because of freezing and thawing during the work. The assistance to interpretation of resistivity-measurements from previously drilled holes at this site was negative. At this dam-site 71 resistivity-measurements were made after which a number of holes were drilled. Two cross-sections based on the drill-holes were prepared by E. B. Eckel, a geologist of the United States Geological Survey, and cross-sections based on the resistivity-measurements have been plotted for comparison.

Figure 2 shows the ground-surface, ground-water level, the rock-level as estimated from resistivity-measurements, and the rock-level as shown by drilling. In general, this Figure shows that in the interpretation of the resistivity-measurements the ground-water level probably was mistaken for rock except at station 12, which is close to the river. There was a large variation in depth to rock along the lines at stations 4 and 6, which explains in part the errors at these stations. The measurements shown on this cross-section were the first measurements made at this dam-site.

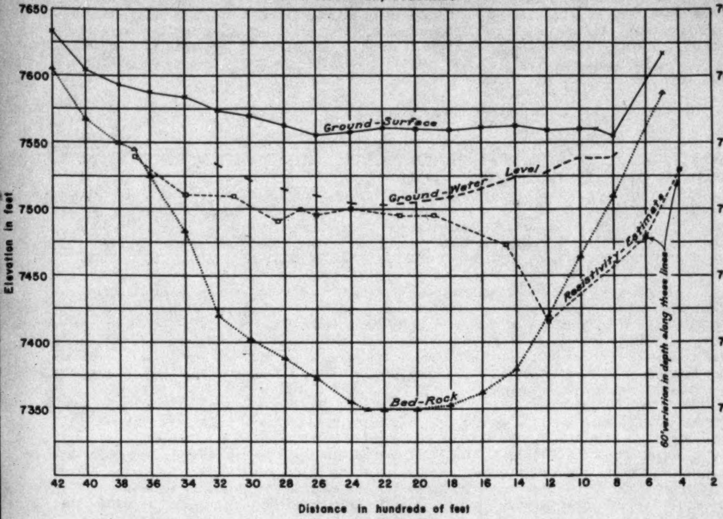
CROSS-SECTION of DAMSITE
NEVADA CREEK, MONTANA

Figure 1



CROSS-SECTION at DAMSITE
PINE RIVER, COLORADO

Figure 2



CROSS-SECTION at DAMSITE
PINE RIVER, COLORADO

Figure 3

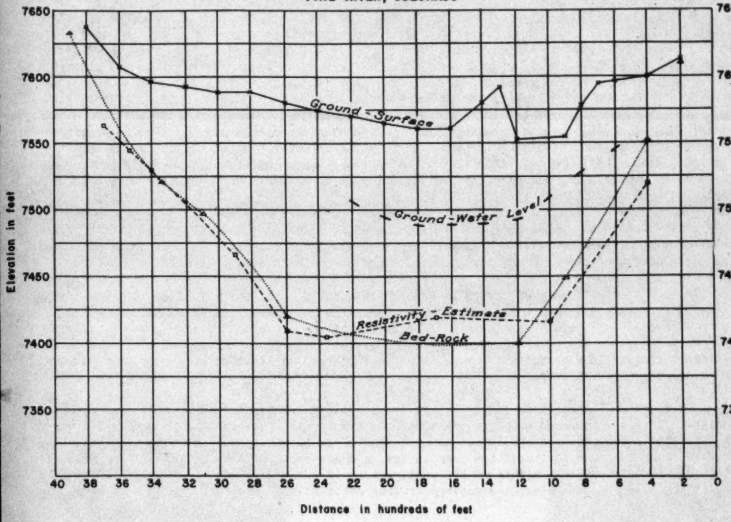


Figure 3 shows another cross-section at the same dam-site. Here the interpretation follows very closely the actual rock-surface. These measurements were made after those shown in Figure 2 and after the geologists had begun to realize that the depth to rock was greater than was at first assumed. All the interpretations were made before drilling except for the two drill-holes mentioned above. Owing to the heavy cover of snow it was difficult to locate rock-exposures from which to obtain the resistivity of the bed-rock. This condition interfered greatly with an accurate interpretation of results.

The man who made the measurements wrote me in part as follows:

"In my opinion the results at the Pine River Dam-Site are not to be considered representative of those that can be expected from the resistivity-method, because violence was done to practically every principle that should guide the operation of that method. There was no geologic map and no control by information from drilling because of failure to get the holes down. Only one formation-test was obtained, and that on an arkose in which the ground-water was frozen. Knowledge of resistivities of the formations was thus wholly inadequate. Failure to obtain these resistivities is probably the most serious charge that can be placed against winter working conditions. So we cannot use these results as representative of what can be obtained."

However, even with these unsatisfactory conditions one cross-section is excellent. The other cross-section illustrates an error that can be made anywhere, through assuming that a change in resistivity is due to rock when it is due to some other material. In this place the error might not have been made if the snow-cover had not prevented tests on the formation. This work also seems to show that if a large number of measurements are made the geologist becomes more familiar with conditions and will probably make better interpretations than if only a few measurements were made.

Although in this work the ground-water was discovered unintentionally, no experience is available to show that it can be located consistently when its depth is unknown. At one site near a river, where the altitude of the water-surface in the river was known, the ground-water in a buried channel was indicated very plainly at about the same altitude. This water was at a depth of over 100 feet. Experience indicates that it would be difficult to determine the presence of ground-water directly, but if it is known to be present and its approximate altitude is known it can probably be located on a resistivity-curve and traced to adjoining areas.

If only those determinations at the Pine River Site that clearly indicated the depth to rock and not the depth to ground-water are considered, the average error in such determinations is about 20 per cent. At Nevada Creek the error was about 23 per cent. On one line on the Pine River the depth to rock in one direction from the center along a resistivity-line was 20 feet and in the other direction it was 60 feet. This difference in depth was noted in the interpretation of the curve and confirmed by drilling. So where the depth to rock may be so variable an error of 20 per cent at a given point is not considered prohibitive when it is considered that the readings represent average conditions for a considerable distance each side of the center. At the Pine River Dam-Site, even with all its shortcomings, the estimates derived by resistivity-measurements came much closer to the truth as to depth to bed-rock than did the estimates from the hasty preliminary geologic examination. Also there was an alternative dam-site farther down the Pine River which was discarded without drilling at least partly on the basis of the resistivity-measurements.

At the Grand Coulee Dam-Site on the Columbia River in Washington, where granite underlies an overburden of sand, gravel, and clay, four measurements were made in 1932 at drill-holes, and the depth to rock probably could have been estimated from these curves to within 10 per cent.

The source of the largest errors in depth-determinations of bed-rock comes from the assumption that a break in the curve is due to rock whereas it is caused by some other material. If the rock has a high resistivity there is less danger of this error. But if the resistivity is low and the resistivity of overburden and rock are nearly the same, this possibility should always be carefully considered, and estimates of depth should be regarded with suspicion unless drill-holes are available for comparison.

Where reliable records from drill-holes are available for comparison or where the rock has a high resistivity compared with the overburden, the error in cross-section of a dam-site based on resistivity-measurements should not be more than 10 to 20 per cent. Where no drill-holes are available and the resistivity of the rock is low, a cross-section based on resistivity-measurements should be correct to within 20 per cent, but it is subject to suspicion unless there is supporting evidence in the surface-geology or from drill-holes. Accuracy can usually be increased by increasing the number of measurements and comparing results, but this of course increases costs. The accuracies mentioned above appear to be sufficient for use in outlining buried channels in connection with ground-water studies and probably are sufficient also for estimates of depths to gravels that might contain water.

The overburden at dam-sites usually includes gravel and boulders, and the cost of drilling in such material can be estimated roughly at $4 to $5 a foot. The cost of depth-determinations by resistivity-measurements averages about $30 each. For depths of less than 50 feet the cost will be somewhat less. Cost depends on the topography, amount of brush or trees, and the ease with which the bed-rock can be identified. The cost of depth-determinations by resistivity-measurements is therefore very much less than by drilling.

The results that may be expected from resistivity-measurements at dam-sites can be summarized as follows:

(1) The better of two alternative dam-sites can usually be determined without drilling.
(2) The presence or absence of buried channels can usually be determined.
(3) The character of terraces can be predicted.
(4) The depth to bed-rock can be approximated and contour-maps of the bed-rock surface drawn. This estimate must be checked by drilling, but a combination of drilling, geologic studies, and geophysical work will give cheaper, quicker, and more accurate results than drilling alone.

The last three advantages would be useful in hydrologic studies.

U. S. Geological Survey,
Washington, D. C.

SEARCH FOR GROUND-WATERS BY THE ELECTRICAL RESISTIVITY-METHOD

L. E. Workman and M. M. Leighton

In 1931, the Illinois State Geological Survey instituted an investigation of the possibilities of the electrical resistivity-method in discovering and tracing subsurface water-bearing deposits of sand and gravel. This was carried on by M. King Hubbert and considerable success was attained (Results of earth-resistivity survey on various geologic structures in Illinois, Amer. Inst. Min. Met. Eng., Tech. Pub., No. 463, 1932). Since then the method has been extensively used and, although not infallible, it has been of great value to cities and villages that have heretofore found it difficult to obtain sufficient ground-water supplies.

Practically all of the resistivity-surveys conducted in Illinois to locate supplies of ground-water have been situated in the central portion of the State, where glacial drift mantles the shales, thin sandstones, limestones, and coals of the Pennsylvanian system. No ground-water suitable for municipal supplies can be found in the Pennsylvanian rocks of this area so that the only possible source is the glacial drift.

Method of survey--The instruments used in these surveys were the Megger ground-tester and the Gish-Rooney resistivity-instrument. Briefly, the principles involved in the use of both instruments are as follows: When an electrical current is passed from the instrument through the ground between two current-electrodes, the resistance of the ground to the current may be tested by tapping into the ground-circuit by means of two other electrodes placed in line with the current-electrodes and observing the loss of potential between these two inside points.

The entire resistance of the ground between the two current-electrodes is expressed by the equation

$$R = E/I$$

in which R is the resistance in ohms, E the voltage, and I the amperes of current.

F. Wenner (A method of measuring earth-resistivity, Nat. Bur. Stand., Bull. 258, 1916) demonstrated that when the four electrodes are equally spaced apart in a line, the specific resistivity of a unit-volume of the ground may be obtained by the equation

$$P = 2\ aE/I$$

in which P is the specific resistivity of the earth expressed in ohms per cubic centimeter and a is the distance between the two inside, or potential, electrodes expressed in centimeters. The separating distance between two successive electrodes is theoretically the depth to which the specific earth-resistivity is determined.

The method of conducting the survey at any locality is to cover the area with a grid of traverses in which the earth is tested to approximately the base of the glacial drift or to a known water-bearing sand-and-gravel deposit. At significant locations, depth tests are made by progressively widening the electrode-spacing to test for the presence, depth, or thickness of a subsurface deposit having high resistivity. The graphic representations of the traverse-tests and of the depth-tests are known, respectively, as the traverse-profiles and the depth-profiles.

Ground-conditions affecting resistivity-measurements--Beside the careful manipulation of the instrument itself during the survey, there are a number of facts with regard to resistivities that must be kept in mind in conducting and studying the results of these resistivity-surveys:

(1) Shale and glacial till give lower resistivities than do sandstones, limestones, sands, and gravels. The resistivities of Pennsylvanian shales are commonly 3000 to 4000 ohms per centimeter, while the resistivities of till run a little higher, being 4000 to 5000 ohms per centimeter. On the other hand, the resistivities of sand and gravel vary considerably from 10,000 to 30,000 ohms per centimeter. The resistivities of loose sandstone are probably of the same order.

(2) Glacial till, sand, and gravel have all degrees of compaction from compact clay to coarse, loose gravel, with corresponding effects on the resistivities.

(3) The resistivity-value to any certain depth is not a measure of the resistivity of the material at that depth only, but rather is the average resistivity of all the materials to the depth tested. Thus, a 5-foot gravel-deposit at a depth of 50 feet makes a much more pronounced showing than a similar deposit at a depth of 300 feet.

(4) Specific resistivities are not so much functions of the relative compaction of the materials as of the chemical content of the water in the deposit, as explained by Karl Sundburg (Effect of impregnating waters on electrical conductivity of soils and rocks, Trans. Amer. Inst. Mech. Eng., Geophys. Prospecting, 1932). Dry minerals are very poor conductors, so that a dry sand- or gravel-deposit gives especially high resistivity-values, which should not be interpreted as being an especially promising water-bearing deposit. Likewise, a thick layer of loose, dry soil is likely to unduly increase resistivity-values. Variations in the chemical content of water in a single deposit from one place to another are likely to be misinterpreted as variations in compactness of the materials.

(5) When tests are being made to include the entire thickness of the glacial drift, variations in the thickness of the drift due to present surface or preglacial surface-irregularities may allow bed-rock sandstone or limestone to come within the field of the current and produce high resistivity-values which may be wrongly interpreted as water-bearing sand and gravel.

Specific surveys

Some specific cases illustrating surveys in Illinois are given herein.

Raymond--Raymond is located in a region where adequate ground-water supplies are uncommon because the glacial drift is thin and has few sand-and-gravel beds. Five unsuccessful test-holes had been drilled in the village before the State Geological Survey was requested to make a resistivity-survey. Bed-rock had been encountered at depths of 19 to 55 feet. The area was covered by a grid of traverses extending to a maximum of two miles beyond the limits of the village. Resistivities were measured to 50 feet.

The resistivity-curves over most of the area showed a fair regularity between 2000 and 4000 ohms per centimeter. However, four parallel east-west traverses (Fig. 1), a half mile to a mile apart, outlined an area about 2000 feet wide, extending in a south-southwest direction about 3/4 mile east of the limits of the village in which resistivity-values rose from 4000 to 7000 ohms. Depth-profiles taken at significant locations indicated that a deposit giving high resistivity lay near the surface extending to depths of 25 to 40 feet.

This appeared to indicate a preglacial channel containing outwash sand and gravel. A location for a test-hole was recommended at the top of the high nearest the center of the village.

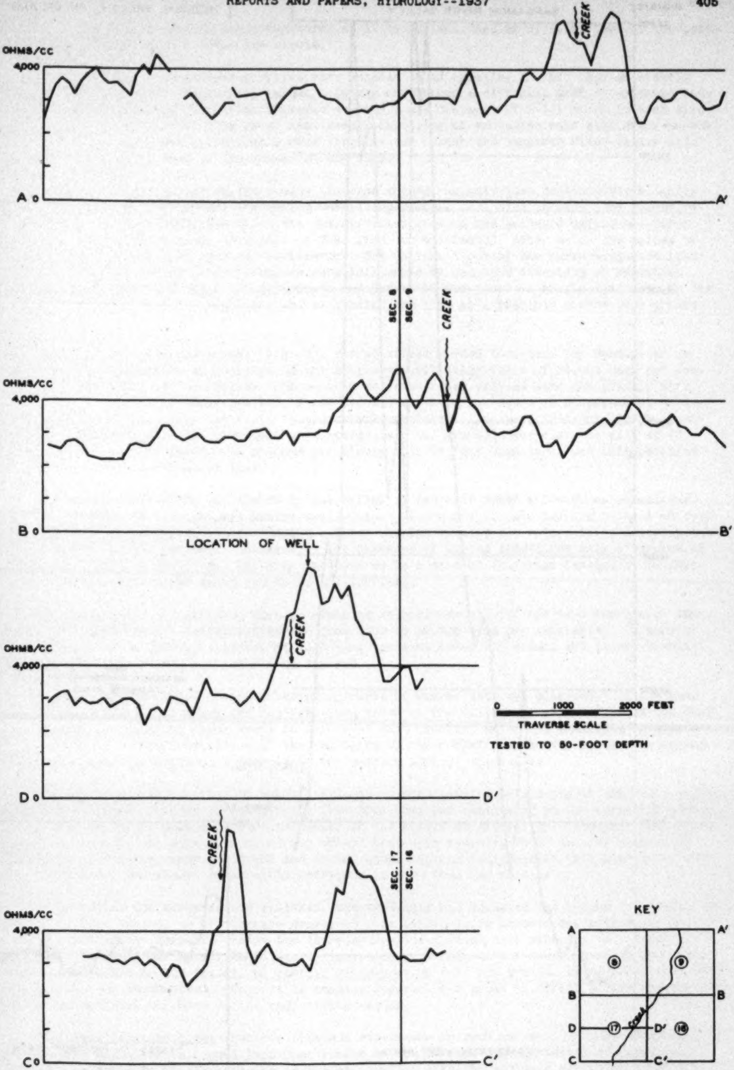


FIG. 1 — RESISTIVITY-TRAVERSE PROFILES AT RAYMOND, ILLINOIS SHOWING LOCATION OF WELL

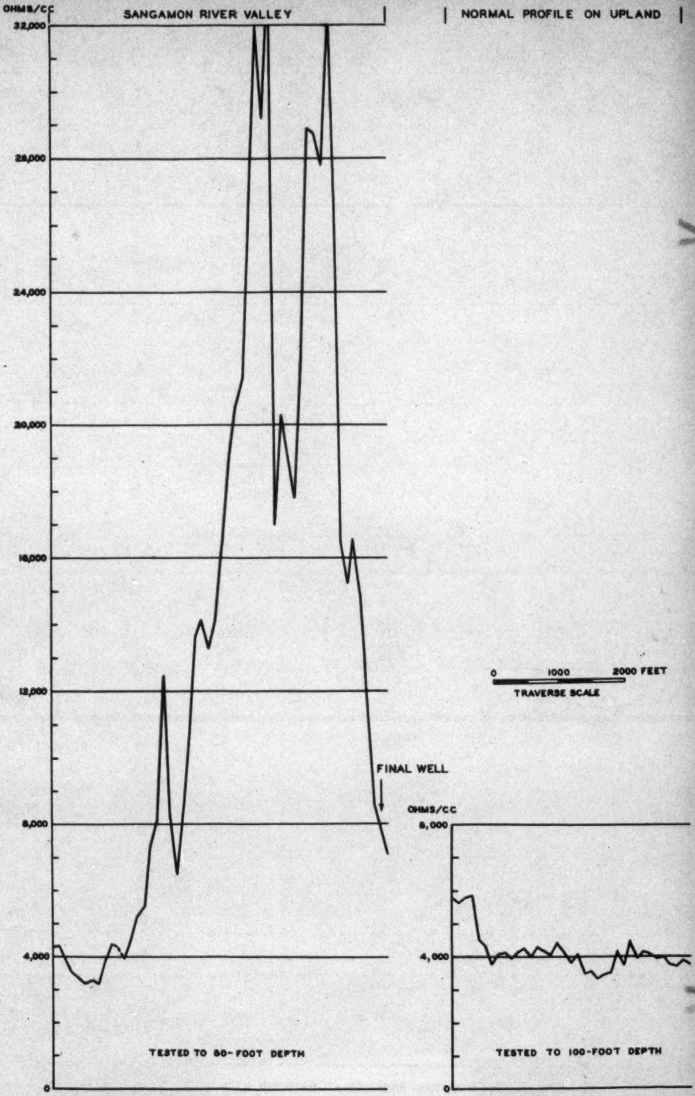


FIG. 2—RESISTIVITY-TRAVERSE PROFILES NEAR ATHENS SHOWING HIGH RESISTIVITY IN SANGAMON RIVER VALLEY, NORMAL RESISTIVITY ON UPLAND, AND LOCATION OF FINAL WELL

Water-bearing sand and gravel was encountered at 17 to 30 feet, and an official test of the test-hole showed 100 gallons of water per minute.

Athens--The Athens traverse-profiles were especially interesting in that they so clearly showed three heights of resistivity-values. It was considered a difficult area in which to find a ground-water supply and the first traverse was run for a distance of 2-1/2 miles in each direction from the center of the City in an east-west line hoping to encounter some high areas worthy of further testing. Also a traverse a mile long was run across the Sangamon River Valley situated over three miles west of the center of the City.

The western three miles of the 5-mile traverse showed resistivities consistently slightly below 4000 ohms per centimeter, indicating underlying glacial till with perhaps some Pennsylvanian shale. In the eastern two miles the resistivities rose to the eastward during the first mile in a quite regular slope to a peak of 7000 ohms per centimeter, after which the values varied between 5000 and 7000 ohms per centimeter. The uniform slope of the curve suggested that in the eastern portion resistivity-values were influenced by bed-rock limestone or sandstone which probably lay higher than 100 feet depth and dipped to the east. A single test-hole in the high area proved this to be sandstone and eliminated the high as a possible source of a ground-water supply.

The profile across the valley (Fig. 2), showed values around 4000 ohms per centimeter on the bordering uplands and an increase to the extraordinarily high value of 34,000 ohms per centimeter in the middle of the valley. This could be interpreted only as sand and gravel, with the possibility that the upper portion of the deposit may be dry. Since 12 unsuccessful test-holes had been drilled near the City, it was finally decided to locate a test-hole on the eastern edge of the valley. The test-hole encountered sand and gravel under clay and silt at 48 to 60 feet depth which yielded 90 gallons per minute with 22 feet draw-down, and this location was selected for the permanent well.

Petersburg--Petersburg is located in the valley of Sangamon River a few miles downstream from the location of the proposed Athens Well. Since Petersburg already had a good well 48 feet deep, the problem consisted not in finding a water-bearing deposit but rather in determining the best location for the new well. Because of the presence of buried pipe-lines only a portion of the village could be surveyed. The area was covered by a grid of traverses testing to 50 feet depth, several depth-tests being run to 50 and 100 feet.

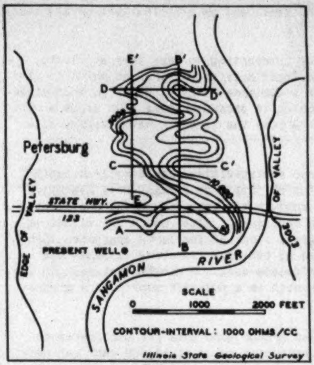
The depth-profiles indicated that in areas of highest resistivity the sand and gravel lay at 25 to 50 feet depth. Resistivities ran from 5000 to 10,000 ohms per centimeter. A contour-map (Fig. 3) with a contour-interval of 1000 ohms per centimeter was drawn, and it was readily apparent where the second well should be located.

Heyworth--At Heyworth, a very interesting curve of resistivity was obtained. It had been found necessary after a survey and test-drilling close to the village to go about two miles west to the valley of Kickapoo Creek where it was known that abundant water was available in glacial outwash gravels. Simultaneously with the beginning of the resistivity-survey across the valley, a test-hole also was begun on a terrace in the eastern part of the valley.

The traverse-profile (Fig. 4) about 1-1/2 miles long, testing to a depth of 100 feet, showed a gradual eastward increase in resistivity from 5000 ohms per centimeter on the bordering uplands west of the valley to 9000 ohms per centimeter in the middle of the valley. Eastward the values decreased in about the same type of curve, except that upon reaching 7000 ohms per centimeter there was a sudden increase to 12,000 and 13,000 ohms. Values continued at this high level for about 1000 feet, and almost as abruptly decreased to 6000 ohms per centimeter.

By this time the traverse was finished, the test-hole had revealed the reason for the extraordinarily high values. A dry terrace gravel 18 feet thick, lying below a dry soil cover of 6 feet, had caused the anomaly. Below the terrace-deposit, glacial till extended to a depth of 100 feet. On the other hand, when a second test-hole was drilled near the peak of the 9000-ohm high in the middle of the valley, 60 feet of water-bearing sand and gravel, lying under six feet of alluvium, was encountered. Thus it is readily apparent how great an effect a thin deposit of dry porous material may have on the resistivity-values.

Important considerations--Besides previous experience in such surveys, an understanding of the geologic situation is a most important factor in the correct interpretation of resistivity-data. It is the duty of the surveyor to become familiar with the geologic situation at each lo-



Illinois State Geological Survey

FIG. 3

RESISTIVITY-SURVEY AT PETERSBURG, ILLINOIS SHOWING CONTOURS OF EQUAL RESISTIVITY AND LOCATION OF PRESENT CITY WELL

cality as revealed by reports, maps, and well-records. Well-records must be collected in the field. If possible, the bed-rock surface should be contoured and the locations of known water-bearing deposits plotted. In the use of the data, it must be kept in mind that well-reports are full of uncertainties and often misleading, due to the fact that drillers' logs and reports from owners are usually inadequate or are open to various interpretations. Well-owners are prone to be overenthusiastic about their wells and the information they furnish should receive candid consideration.

During the drilling of test-holes, a careful comparison of test-hole data with the geologic and resistivity-data is necessary. Each test-hole should be sampled at intervals of five feet or less and the samples studied in the subsurface laboratory. The resulting logs will guide in the location of each succeeding test-hole or the proper location and development of the final well.

Summary of results

As previously stated, practically all areas surveyed were located where it was considered difficult to find sources of ground-water supplies. However, in the total of 24 areas, the following results were obtained;

(1) Eleven municipalities obtained adequate ground-water supplies.

(2) One municipality obtained an inadequate ground-water supply which was, nevertheless, acceptable.

(3) Three projects, all showing good prospects, are to be tested by the drill in a short time.

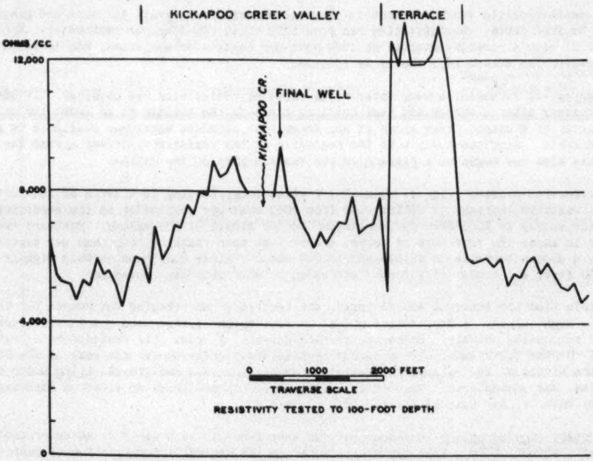


FIG. 4—RESISTIVITY-TRAVERSE PROFILE AT HEYWORTH SHOWING EFFECT OF TERRACE-DEPOSIT AND LOCATION OF FINAL WELL

(4) Two areas having good prospects were not tested due to financial difficulties of the villages.

(5) One area, in which very good prospects for a certain large city were found, was surveyed in connection with a quadrangle report by the State Geological Survey without likelihood of its being tested in the near future. This survey was valuable in delineating the preglacial drainage-pattern.

(6) In five areas the resistivity-surveys and test-drilling proved that ground-water was not available within a reasonable distance of development.

(7) In one area the resistivity-survey indicated that the prospects were poor and, as the result, no test-holes were drilled.

Thus, the results give cause for increasing confidence in the reliability of the earth-resistivity method as an aid to the search for subsurface water-bearing deposits in the glacial drift in Illinois. It offers a wide field for service to numerous municipalities that wish to develop more adequate ground-water supplies. At the same time, as a means of tracing out gravel-filled preglacial channels and otherwise helping to solve the intricate problems of glacial geology, it is likely to prove of great importance in the future.

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PROSPECTING FOR WATER WITH GEOPHYSICAL METHODS

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Because of the absence of the author, this paper was abstracted only for the Washington meeting. It was communicated in full by him at the regional meeting in Denver and therefore appears in these Transactions under the proceedings of that meeting.

MAXIMUM STREAM-FLOW WITH REFERENCE TO FLOOD-FORMULAS

C. S. Jarvis

An echo of the remote past was discernible during a recent review of plans for a small headwaters-reservoir by a public agency. The field-representative had provided a spillway-capacity of only 50 second-feet per square mile, where mature judgment and broad experience of the reviewers disclosed that 1000 csm should be the basis of design.

Does this mean that the tragic flood-experiences of recent years have been forgotten? No; one of the virtues of present procedure is reflected by the review and amendment of the field-plans, instead of building according to the first crude conception.

Again public interest has been stimulated in flood-control as a national, State, or regional problem, as opposed to the notion of its local and restricted significance. Again we hear the apparently simple yet obviously impractical solution proposed, namely, to vacate the valleys and to let the raging waters proceed without hindrance in their established channels and over their natural flood-plains. And as resolutely as ever, man undertakes to work out the best combination of plans, often a compromise representing protective works, channel-enlargements at critical sections, stream-regulation through storage in either underground or surface reservoirs, and flood by-passes or relief channels.

Renewed interest in flood-phenomena and potentialities have naturally followed the record-breaking floods of the past decade which exceeded those of 1889 at a number of stations in the northeastern section of the United States. Incidentally, such recurrences after about 47 years recall the theory widely held among meteorologists and hydrologists that from 35 to 50 years may suffice to develop a fairly comprehensive view of rainfall and runoff potentialities, if the records are continuous and accurate.

The quest for knowledge and the vital need for its practical application have brought forth devices for extending the trends of known facts into fields of the unknown. With each notable contribution of basic data there are opportunities disclosed for extension or refinement of earlier generalizations, and for better use of accumulated records. Thus, in the course of providing fairly adequate, well-proportioned flood-channels and cross-drainage structures for our early railway and highway development, the pioneers in those fields of engineering construction made use of the scattering, fragmentary hydrologic data then available, and endeavored to establish general rules or standards for their own guidance.

Among the relationships sought were the influence of drainage-area, shape of basin, surface- and channel-slopes, soil-characteristics, vegetal cover, and other physical factors on the intensity of flood-runoff resulting from severe storms normally expected within the locality under consideration. Many of those early concepts and estimates were fair approximations according to more recent observations, experience, and analysis.

Efforts to extend the trends of the meager hydrologic data resulted in the devising of dozens or scores of proposed formulas, some of them representative of one climatic region or drainage-basin, and others as divergent as the weather-phases and runoff-characteristics throughout a broad country or a continent. No wonder most of the general formulas thus proposed for floodways have been largely disappointing if not misleading, while only a few have achieved well-deserved recognition and practical use in restricted regions.

Intent on an unbiased, deliberate, comprehensive, and critical examination and testing of flood-formulas and tabulations as found in technical literature throughout the world and in local official practices in many countries, the writer has spent a period of several years intermittently on this investigation, reaching the conclusion that one of the earliest published American expressions, the Myers formula for floodways, was best adaptable for expansion to cover the entire field of practice (Flood-flow characteristics, Trans. Amer. Soc. Civil Eng., v. 89, pp. 985-1104, including discussions, 1926). Repeated confirmation has come from independent, authoritative sources as to the basic relationship between drainage-area and maximum flood-flow as derived from the Myers formula, to the effect that the runoff-yield per square mile during peak flood-flow from areas generally similar as to climatic and physical conditions varies inversely as the square root of the number of square miles.

Probably the most notable early test was applied by the special committee of the American Railway Engineering Association, 1909 to 1912. The final conclusion was that no existing formula could be recommended for general application, but that Dun's tables best represented the relation between drainage-area and runoff.

One of the most recent tests deserving mention is that of the Boston Society of Civil Engineers, following the New England floods of November 1927. Their expression for maximum flood-flows in New England represents about 80 per cent on the Myers scale, as compared with nearly 20 per cent for Dun's tables, and 10 per cent for the original Myers formula, all varying inversely as the square root of the drainage-area if reduced to csm. The Boston Society of Civil Engineers also made use of a transformed expression, providing a sliding scale to represent the runoff depth over the drainage-basin, but assuming an 8-inch maximum for New England conditions (U. S. Geol. Sur. Water-Supply Paper 771, p. 39).

A further confirmation of Myers' formula appears in Figure 5 of Engineering News-Record, December 10, 1936 (p. 826), in connection with the staff article on Water-Conservation and Flood-Control in the Tennessee Valley. The envelope curve there shown evidently rates somewhat higher than 50 per cent on the Myers scale for all the notable flood-data assembled and plotted thereon from storms as early as 1889 and as late as 1935, in the northeastern section of this country.

In order to compare and evaluate recent flood-events, Figure 1 has been prepared, with Table 1 as an index for the several items there plotted and numbered. Inasmuch as many records were broken by the floods of 1935, 1936, or 1937, both the maximum and the next highest flood have been plotted on a single vertical line for each of several stations, the superseded maximum being marked by the caret. Thus, in March 1936, the Ohio River at Pittsburgh, and in January 1937, the same River at Cincinnati, Louisville, and Paducah has apparently exceeded previous records by about 15, 40, 38, and 16 per cent. Likewise, the Susquehanna at Harrisburg in March 1936 exceeded the peak of June 1889 by about five per cent, while the Williamsport peak-flow was about 1.7 per cent lower than that of 1889.

Figure 1 and Table 2 include some of the most notable of the high flood-yields yet recorded and authenticated, as well as some which are mere approximations and therefore subject to considerable revision. The scarcity of data for small areas reflects the lack of facilities for collecting such information, rather than their freedom from intense flood-flows.

Table 1--Examples of record-breaking floods of 1935, 1936, or 1937 which represent the best available data as of April 28, 1937

(Percentage of excess shown in last column in parentheses)

Item No.	Stream and station	Drainage-area	Period of record	Date of maximum	Calendar-day discharge		Momentary peak-discharge		Myers scale
		sq mi	years		cfs	csm	cfs	csm	o/o
64	Kiskiminetas River, Avonmore, Pa.	1723	1907-1936	Mar 1936	......	....	200000	116	48.2 (116)
78	Susquehanna, W. Br., Williamsport, Pa.	5682	1895-1936	Mar 1936 Jun 1889	....	....	313000 318000	55.1 56.0	41.5 42.2 (1.7)
81	Potomac River, Pt. of Rocks, Md.	9654	1895-1937	Mar 1936	434000	45.0	484000	50.2	49.3 (42)
82	Republican River, McCook, Nebr.	10000	1931-1936	May 1935	245000	....	245000	24	24.5 (500)
84	Potomac River near Washington, D. C.	11560	1930-1937	Mar 1936	......	....	460000	40	43.0 (40)
86	Ohio River, Pittsburgh, Pa.	19106	1854-1937	Mar 1936	......	....	550000	29	38.8 (16)
89	Susquehanna River, Harrisburg, Pa.	24100	1786-1937	Mar 1936	......	....	740000	31	47.5 (5)
90A	Brazos River, Waco, Tex.	28500	1884-1937	Oct 1936	......	....	255000	9	15.2 (91)
95	Tennessee River, near Buchanan, Tenn.	39700	1930-1937	Jan 1937	......	....	370000	9.3	18.6 (26)
97	Ohio River, Cincinnati, Ohio	75800	1858-1937	Jan 1937	......	....	950000	12.5	34.4 (43)
99	Ohio River, Paducah, Ky.	202700	....	Jan 1937	......	....	1850000	9.1	41.1 (52)

The graphs of flood-formulas plotted in broken lines on Figure 1, reading progressively from the lowest curve, include Kuichling's frequent floods; Kuichling's rare floods, requiring two equations to cover the field; the formula suggested by I. Gutman in Engineering News-Record of October 1, 1936 (p. 474); an envelope-curve covering nearly all of the authenticated flood-maxima, representing a modification of Myers scale for 150 per cent (the addition of the quantity "3" in the denominator); and an expression six times that suggested by Gutman, as shown in Engineering News-Record of November 5, 1936 (p. 655). The evident defect of this last-named curve is being fully five times as high as required among small areas, and being lower than many of the data among the larger basins. Also, the intersection of the Kuichling curves by two of the others indicates their non-applicability among large drainage-areas.

Items 62, 71, and 82, for three gaging-stations on the Republican River rating 26.0, 29.9, and 24.5 per cent, respectively, on Myers scale, and thus six to seven times the previously observed maximum intensity, are among the lowest plotted values, or one-third to one-fifth of the world-record maxima for the same extent of drainage-area in each case.

In view of all available records of rainfall and runoff for the regions concerned, it appears probable that the Republican River Flood of May 1935 approached the ultimate flood-potentialities of that basin more closely than did the Potomac River, rating about 43 per cent on Myers scale in March 1936 as well as in June 1889 according to latest revisions; or Devils River near Del Rio, Texas, rating 88 per cent in September 1932; or the Cagayan River, Island of Luzon, Philippine Islands, when it rated approximately 153 per cent on December 4, 1936.

In accordance with experience of most investigators in the field of hydrology as related to flood-phenomena, the yield-curves should level off for small areas, indicating that the first power of the drainage-area should be used, rather than a fractional power for headwaters. This break in alignment might occur anywhere between two and ten square miles, according to local conditions; but it is convenient to adopt four square miles as the limit below which the peak-flow should be directly proportional to the area, and consequently 5000 csm as representing 100 per cent on the Myers scale for these small areas.

Consideration of flood-flow potentialities should naturally begin with small areas and with times of concentration so short as to allow but slight opportunities for infiltration and other forms of detention or storage to regulate the flow. Well-authenticated records of rainfall having occasionally exceeded 0.8 inch in five minutes, four inches per hour, six inches in three

Table 2--Maximum record-flood discharges of selected streams

Serial No.	Stream and station	Drainage-area	Period of record	Date of maximum	Calendar-day discharge		Momentary peak discharge		Myers scale	Main reference[a]
		sq mi	years		cfs	csm	cfs	csm	o/o	
1	Bull's Run, Long Level, Pa.	0.58	....	Jul 1914	.....	...	2420	4170	83.4	F
2	Mann's Run, Creswell Station, Pa.	0.60	....	Jun 1917	.....	...	2400	4000	80.0	F
3	Manoa, W. Br., Oahu, H. I.	1.00	....	Jan 1921	.....	...	3250	3250	65.0	F
4	Manoa, E. Br., Oahu, H. I.	1.10	....	Jan 1921	.....	...	3090	2810	56.2	F
5	Mad Creek, Leroy, N. Y.	1.50	....	May 1916	.....	...	3450	2300	46.0	F
6	Indian Run, Letort, Pa.	2.1	....	....	.....	...	4153	1930	38.6	F
7	Missouri Canyon (mouth T6N, R70W), Colo.	2.4	....	Jun 1923	.....	...	4350	1810	36.2	U
8	Glen Creek, near Townsend, N. Y.	2.91	....	Jul 1935	.....	...	7330	2520	50.4	N
9	East Hay Creek (Washita Basin), Okla.	4.0	....	Apr 1934	.....	...	6400	1590	31.8	U
10	Honey Cr., E. Fork, New Carlisle, Pa.	6.7	....	Jul 1918	.....	...	14800	2210	57.2	F
11	Cameron Arroyo, near Pueblo, Colo.	7.3	....	Jun 1921	.....	...	13900	1900	51.4	F
12	Saw Kill, near Shady, N. Y.	9.5	....	Jul 1935	.....	...	9180	966	29.8	N
13	Orbicella, Italy	10.0	....	Aug 1935	.....	...	20100	2010	63.4	E
14	Trumansburg Cr., Trumansburg, N. Y.	11.5	....	Jul 1935	.....	...	17800	1550	52.5	N
15	Alazon Cr., San Antonio, Tex.	17.1	....	Sep 1921	.....	...	25900	1515	62.6	F
16	Orba River, Martina, Italy	18.3	....	Aug 1935	.....	...	34200	1870	80.0	E
17	Martinez Cr., San Antonio, Tex.	19.6	....	....	.....	...	23900	1223	54.1	F
18	Willow Cr., near Heppner, Ore.	20.0	....	Jun 1903	.....	...	36000	1800	80.5	F
19	Glen Cr., Watkins Glen, N. Y.	21.3	....	Jul 1935	.....	...	27900	1310	60.5	N
20	Wailua, near Lihue, Kanai, H. I.	23.0	....	Jan 1921	.....	...	45000	1955	93.7	F
21	Apache Creek, San Antonio, Tex.	23.8	....	Sep 1921	.....	...	22600	948	46.3	F
22	Olmos Creek, San Antonio, Tex.	26.4	....	Sep 1921	.....	....	25000	948	48.6	F
23	Morgan Cr., near Chapel Hill, N. C.	27.0	....	Aug 1924	.....	...	30000	1110	57.6	G
24	Dudley Cr., near Lisle, N. Y.	29.6	....	Jul 1935	.....	...	16200	547	29.9	N
25	San Antonio Cr., San Antonio, Tex.	34.3	....	Sep 1921	.....	...	23700	691	40.5	F
26	Sergeant Major Cr., Okla.	37.0	....	Apr 1934	.....	...	53650	1450	87.6	U
27	Orba at Valle Orbicella, Italy	42.0	....	Aug 1935	.....	...	54600	1300	84.3	E
28	East Quartermaster Creek, Okla.	41.5	....	Apr 1934	.....	...	54800	1320	85.2	U
29	Nine Mile Creek, Okla.	42.0	....	Apr 1934	.....	...	36100	860	55.7	U
30	Elkhorn Cr., Keystone, W. Va.	44.0	....	Jun 1901	.....	...	60000	1363	90.3	F
31	Meads Cr., E. Campbell, N. Y.	46.1	....	Jul 1935	.....	...	30300	657	44.6	N
32	San Pedro, below Apache Cr., Tex.	46.5	....	Sep 1921	.....	...	32450	698	47.6	F
33	Taughannock Cr., Halseyville, N. Y.	56.7	....	Jul 1935	.....	...	42100	742	55.9	N
34	Orba at Reservoir, Italy	58.0	....	Aug 1935	.....	...	80000	1377	104.8	E
35	Rock Creek, near Pueblo, Colo.	59.0	....	Jun 1921	.....	...	53800	913	70.0	F
36	W. Quartermaster Creek, Okla.	61.0	....	Apr 1934	.....	...	34200	560	43.3	U

37	Chester Cr., near Philadelphia, Pa.	62.0	....	Aug 1843	.....	...	62000	1000	78.7	F
38	San Felipe Cr., Del Rio, Tex.	62.0	....	Jun 1935	.....	...	45000	726	57.1	B
39	Brushy Creek, Round Rock, Tex.	74.7	....	Sep 1921	.....	...	34500	462	39.9	F
40	San Antonio Creek, Tex.	85.0	....	Sep 1921	.....	...	42400	499	46.0	F
41	Otay Cr., Lower Dam, Calif.	98.6	....	Jan 1916	.....	...	37400	379	37.6	F
42	San Jacinto, near San Jacinto, Calif.	108.0	....	Jan 1916	.....	...	30000	278	28.9	F
43	W. Quartermaster Creek, Okla.	108.0	....	Apr 1934	.....	...	69000	640	66.6	U
44	Johnson Cr., near Fish Hatchery, Tex.	111	....	Jul 1932	.....	...	138000	1240	130.5	E
45	Fall Cr., Ithaca, N. Y.	124	....	Jul 1935	.....	...	25800	208	23.1	E
46	Devils Cr., near Viele, Iowa	143	....	Jun 1905	.....	...	85800	600	71.7	F
47	Salado Creek, Salado, Tex.	148	....	Sep 1921	.....	...	143000	966	117.5	F
48	Middle Bijou Creek, below Wilson Cr., Colo.	151	....	May 1935	.....	...	71270	473	58.3	E
49	Seco Cr., 7 mi. above D'Hanis, Tex.	153	....	May 1935	.....	...	254000	1660	205.0	E
50	Ardeche River, Aubenas, France	178	....	... 1890	.....	...	123500	694	92.5	F
51	Kiowa Cr., North of Kiowa, Colo.	190	....	May 1935	.....	...	110000	578	79.8	E
52	W. Bijou Creek, Byers, Colo.	290	....	May 1935	.....	...	168000	580	98.8	E
53	Irrity River, India	336	....	....	.....	...	150000	446	81.6	F
54	Krishna River, India	345	....	....	.....	...	118000	343	63.6	F
55	W. Nueces River, above Brackettville, Tex.	402	....	Jun 1935	.....	...	612000	1520	305.0	E
56	Frio River, Concan, Tex.	485	1923-1936	Jul 1932	41200	84.9	162000	334	73.5	U
57	Santa Catarina, Monterrey, Mexico	544	....	Aug 1909	.....	...	235000	432	100.8	F
58	Guadalupe River, Kerrville, Tex.	570	....	Jul 1932	.....	...	196000	344	82.2	E
59	Ardeche, Rhone Junction, France	831	....	... 1827	.....	...	318000	382	110.0	F
60	Musi River, Hyderabad, India	862	....	... 1908	.....	...	425000	493	145.0	F
61	West Nueces River, above Cline, Tex.	880	....	Jun 1935	.....	...	536000	609	180.0	E
62	Republican River, Newton, Colo.	1270	....	May 1935	.....	...	103000	81	26.0	U
63	Bijou Creek, at Mouth, Colo.	1444	....	May 1935	.....	...	283000	196	74.5	E
64	Kiskiminetas, Avonmore, Pa.	1723	1907-1936	Mar 1936	.....	...	200000	116	48.2	P
65	Llano River, Junction, Tex.	1762	1915-1936	Jun 1935	.....	...	319000	181	76.0	G
66	Obion River at Obion, Tenn.	1880	1929-1937	Jan 1937	.....	...	66500	35	15.3	U
67	American River, Fair Oaks, Calif.	1921	1904-1934	Mar 1928	119000	61.9	182900	95	41.5	G
68	Nueces River, near Uvalde, Tex.	1930	1927-1936	Jun 1935	.....	...	616000	319	140.0	E
69	Miami River, Dayton, Ohio	2510	1892-1937	Mar 1913	.....	...	250000	100	50.0	G
70	Rhine, Lake Constance, Switzerland	2555	....	....	.....	...	123500	48	24.5	F
71	Republican, Benkelman, Nebr.	2580	....	May 1935	.....	...	150000	58	29.9	U
72	Devils River, near Juno, Tex.	2733	1925-1936	Sep 1932	.....	...	370000	135	70.4	E
73	Eel River, Scotia, Calif.	3070	1910-1936	Feb 1915	271000	88.3	290000	95	52.3	G
74	Miami River at Venice, Ohio	3790	....	Mar 1913	.....	...	370000	98	60.8	G
75	Scioto River, Chillicothe, Ohio	3850	1913-1936	Mar 1913	.....	...	250000	65	40.3	G
76	Devils River, near Del Rio, Tex.	4004	1900-1936	Sep 1932	.....	...	558000	139	88.0	E
77	Cagayan River, Luzon, P. I.	4100	....	Dec 1936	.....	...	980000	239	153.0	U

Table 2--Maximum record-flood discharges of selected streams--Concluded

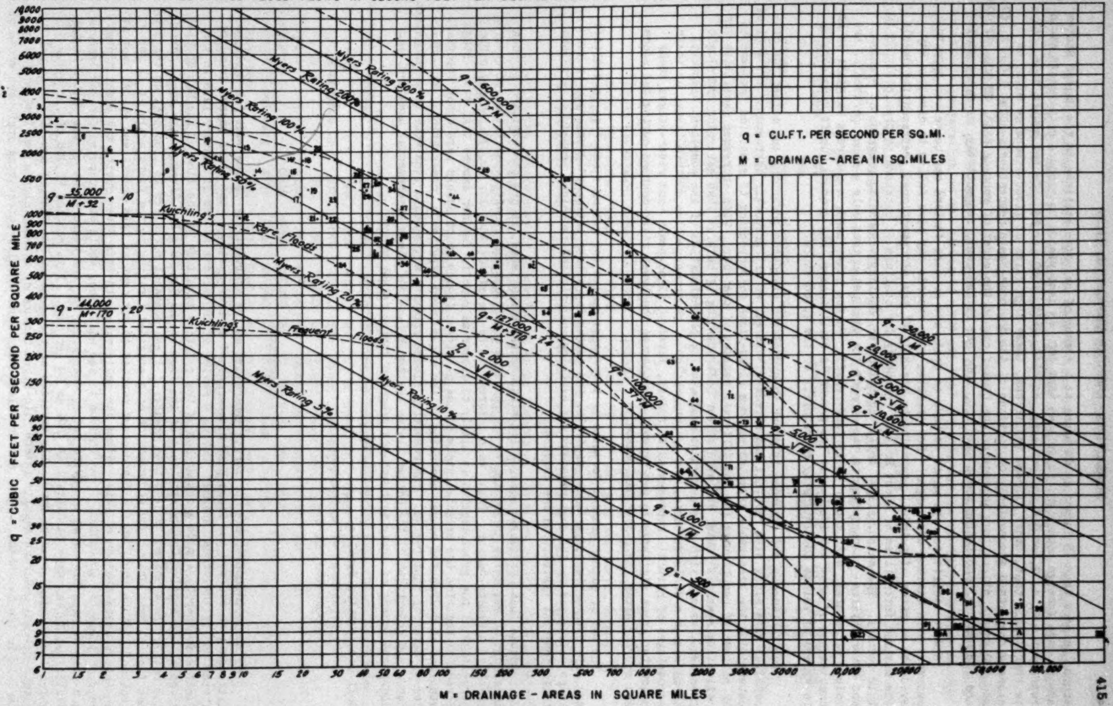
Serial No.	Stream and station	Drainage-area	Period of record	Date of maximum	Calendar-day discharge		Momentary peak discharge		Myers scale	Main reference[a]
		sq mi	years		cfs	csm	cfs	csm	c/o	
78	Susquehanna, W. Br., Williamsport, Pa.	5682	1895-1936	Mar 1936	264000	46.0	313000	55	41.5	P
79	Savannah River, Augusta, Ga.	7304	1884-1936	Oct 1929	315000	43.1	350000	48	40.8	G
80	Muskingum River, McConnelsville, Ohio	7410	1921-1937	Mar 1913	.....	...	270000	37	31.4	U
81	Potomac River, Pt. of Rocks, Md.	9654	1895-1937	Mar 1936	434000	45.0	480000	50	49.0	U
82	Republican, McCook, Nebr.	10000	1931-1936	May 1935	.....	...	245000	24	24.5	U
83	Vaal River, Barrage, South Africa	10000	....	Nov 1917	.....	...	187000	19	18.7	F
84	Potomac River, near Washington, D. C.	11560	1930-1937	Mar 1936	.....	...	484000	42	45.0	U
85	Cumberland River, Clarksville, Tenn.	16000	....	Jan 1937	.....	...	263000	16	20.7	U
86	Ohio, Pittsburgh, Pa.	19106	1854-1937	Mar 1936	.....	...	550000	29	39.8	U
87	Ohio, Sewickley, Pa.	19500	....	Mar 1936	.....	...	574000	29	41.0	P
88	Tennessee, Chattanooga, Tenn.	21382	1874-1937	Mar 1867	393000	18.9	734000	34	50.2	F
89	Susquehanna, Harrisburg, Pa.	24100	1786-1937	Mar 1936	.....	...	740000	31	47.5	P
90	Susquehanna, McCall's Ferry, Pa.	26766	1902-1909	Jun 1889	.....	...	672000	25	41.1	.
				Mar 1904	.....	...	672000	25	41.1	F
				Mar 1936	.....	...	875000	32.7	53.5	U
90A	Brazos River, Waco, Tex.	28500	1884-1937	Oct 1936	.....	...	255000	9.0	15.2	U
91	Po River, Ponte Lagosiuro, Italy	27027	....	....	.....	...	246000	9.1	15.0	F
92	Tennessee River, Florence, Ala.	30800	1894-1934	Mar 1897	430000	14.0	444000	14.4	25.3	F
93	Colorado, Austin, Tex.	38200	....	Jun 1935	.....	...	481000	12.6	24.6	U
94	Danube River, Vienna, Austria	39400	....	... 1501	.....	...	492500	12.5	25.0	F
95	Tennessee River, near Buchanan, Tenn.	39700	1930-1937	Jan 1937	.....	...	370000	9.3	18.6	U
96	Fitzroy River, Australia	58000	....	Feb 1896	.....	...	613000	10.6	25.4	F
97	Ohio River, Cincinnati, Ohio	75800	1858-1937	Jan 1937	.....	...	950000	12.5	34.4	U
98	Ohio River, Louisville, Ky.	90600	....	Jan 1937	.....	...	1100000	12.1	36.4	U
99	Ohio River, Paducah, Ky.	202700	....	Feb 1937	.....	...	1850000	9.1	41.1	U
100	Mississippi River, Memphis, Tenn.	932800	....	Jan 1937	.....	...	1800000	1.9	18.6	U

[a] Symbols and main references are as follows:

B= International Boundary-Commission annual reports (United States and Mexico)
E= Engineering News-Record
F= Flood-flow characteristics, Trans. Amer. Soc. Civ. Eng., v. 89, Table 2, pp. 1003-1024, 1926
G= U. S. Geol. Sur. Water-Supply Papers
N= New York State-Flood of July 1935, U. S. Geol. Sur. Water-Supply Paper 773-E (tabulation of flood discharges)
P= The floods of March 1936 in Pennsylvania (table of flood-records)
U= Unofficial or unpublished hydrologic data

FIG. 1—

MAXIMUM OBSERVED OR ESTIMATED FLOOD-FLOWS IN SECOND-FEET PER SQUARE MILE FOR SELECTED STATIONS WITH RELATION TO PROPOSED FLOOD-FORMULAS



hours, or more than 15 inches in 24 hours at a number of selected stations in the United States and in some foreign countries, it follows that 100 per cent yields to produce peak-runoff would represent 9.6, 4, 2, or 0.6 cfs per acre, or 6140, 2560, 1280, or 380 cfs per square mile. It is conceivable that, under extreme conditions, these high rates of flood-discharge might be closely approached successively on portions of the drainage-basin respectively about 1.0, 15, 60, and 600 square miles, thus accounting for peak-flows of the order of roughly 6140, 39,000, 77,000, and 228,000 cfs, and rating about 123, 100, 100, and 93 per cent, respectively, on Myers scale.

In most localities with which we have to deal, one or more factors may be relied upon to decrease such maximum discharges. For example, long records may have failed to disclose any evidence of rates of rainfall amounting to one-half of the aforementioned, representing nearly the maximum intensities of about 50-year frequency for stations of outstanding precipitation in this country. The shape, slope, soil, vegetal cover, drainage-channels, progress of erosion, and other physical characteristics may warrant the conclusion that only a minor portion of the volume of rainfall will appear as surface-runoff. On the other hand, a moderate rainfall on accumulations of snow and ice, while the ground is still frozen, may produce runoff considerably in excess of volume and intensity of rainfall of the given storm.

Due to renewed and extended interest in hydrologic standards governing the collection of physical data along with rainfall and stream-discharge, we are gradually approaching the goal of determining the reasonably expected maximum flood-flows corresponding to specified frequencies or periods of recurrences for the different seasons of the year. With increased facilities for collecting essential data, and with better understanding of natural laws governing hydrologic phenomena, we may with some assurance evaluate the potentialities of the component elemental areas within a drainage-basin, and by integration of their respective contributions, or their percentages of rainfall represented by runoff, forecast flood-peaks and river-stages among headwater areas similarly to our present practice on the lower river-courses during the storm and shortly after the center has passed.

The use of either general formulas or percentage scales for rating flood-flow intensities may afford valuable comparisons, controls, and checks for either estimated discharges or for those calculated by the most rigorous and exacting analysis and technical procedure, provided their inherent limitations are observed.

Assume that hydrologic observation-stations are established, as now contemplated at such locations as may serve as indexes to the physical conditions and runoff-capabilities of the respective drainage-basins. Then, with information to the effect that 10, 50, 70, or any other percentage of the precipitation is likely to appear as runoff, further assume that river-stage forecasts describe the expected peaks of the gathering floods which should pass other important stations at designated hours, according to the accumulated experience, observations, and analyses of data for that region. The resulting flood-forecasts would be in line with long-recognized needs and objectives of the United States Weather Bureau and other governmental agencies, and along the course of their most notable progress during recent years.

Soil Conservation Service,
U. S. Department of Agriculture,
Washington, D. C.

DISCUSSION

R. S. GOODRIDGE--Could Dr. Jarvis generalize on the adaptability of the modified Myers relationship to express the flood-peak discharges of a river-system as the flood passes down the stream during individual storms? During a review of the severe storms of January 1916 in the Pacific Southwest, I made a comparison of the relative magnitude of the flow of the San Gabriel River in Los Angeles County with that of the flow of the San Luis Rey River to the south where the rain-storm appeared to have been greater. I was somewhat surprised to find that on the 17th the flow at Mesa Grande and at Oceanside both attained a rating on the Myers scale of 17 per cent and that on the 27th the flood-crest reached 40 per cent at both points and 42 per cent at an intermediate station at Pala. Since the scale-values in this River during the great storms held in these two instances, I was curious to see what flood would be indicated for the Henshaw dam-site at Mesa Grande on the Myers rating,determined for the measurement of the United States Geological Survey made at Bonsall in 1891 as 59 per cent. This equaled 85,400 cfs, a value which I concluded could be materially exceeded at the proposed San Gabriel dam-site of equal catchment-area under an equally severe rain-storm because of steeper slopes and less porous materials in the catchment. There are doubtless many other equally interesting instances where it has been found that the Myers scale-rating holds.

Dr. Jarvis stated in reply that in general the Myers relation held for normal streams without dams during the wide-spread storms. In instances where the relationship did not hold there was always a definite reason to which to ascribe the departure therefrom.

At his suggestion, I have prepared tables of a few maximum floods for which data were readily at hand on river-systems and the per cent on Myers scale attained during individual storms as the flood passed downstream. Many more will be available, particularly as soon as the present reports in preparation on the floods of 1936 and 1937 are released by the United States Geological Survey.

San Luis Rey River, California, January 17 and 27, 1916, and February, 1891

Location	Drainage-area	Feb. 23, 1891 flow	Myers scale	Jan. 17, 1916 flow	Myers scale	Jan. 27, 1916 flow	Myers scale	References
	sq mi	cfs	o/o	cfs	o/o	cfs	o/o	
Mesa Grande	209	......	..	24400	17	58600	40	W.-S.P. 426
Pala	322	......	..	.....	..	75300	42	W.-S.P. 426
Bonsall	465	128000	59	.....	..	.....	..	W.-S.P. 447
Oceanside	565	......	..	40000	17	95600	40	W.-S.P. 426

Republican River, Colorado, Kansas, and Nebraska, May, 1935

Location	Drainage-area	Flow	Myers scale	Reference
	sq mi	cfs	o/o	
Newton, Colo.	1264	103000	29	U. S. Army Engineers, B-20-1
Above Benkelman, Nebr.	2707	150000	29	U. S. Army Engineers, B-20-1
Below Benkelman, Nebr.	5134	190000	27	U. S. Army Engineers, B-20-1
McCook, Nebr.	10186	245000	24	U. S. Army Engineers, B-20-1
East of 100° long.	12449	280000	25	U. S. Army Engineers, B-20-1
Bloomington, Nebr.	18670	260000	19	U. S. Army Engineers, B-20-1

A surprising consistency is presented by these figures of the Myers rating. The storm was most severe west of Benkelman, Nebraska. At 100° longitude the rain-storm boundary is reached. This is reflected in diminisned values of the Myers scale as the flood-wave progressed through Bloomington, Nebraska.

Miami River, Ohio, March 25-26, 1913

Location	Drainage-area Gross	Drainage-area Net	Flow	Myers scale	References
	sq mi	sq mi	cfs	o/o	
Above Sidney	498	398	34100	17	Miami Conservancy Dist. Tech. Rep., Part VIII
Sidney	545	445	44000	21	U. S. Geol. Sur. Water-Supply Paper 771, p. 187
Above Loramie Cr.	575	475	48500	22	Miami Conservancy Dist. Tech. Rep., Part VIII
Piqua	842	661	70000	27	Miami Conservancy Dist. Tech. Rep., Part VIII
Tadmor	1128	947	127000	41	Miami Conservancy Dist. Tech. Rep., Part VIII
Dayton	2510	2329	250000	52	U. S. Geol. Sur. Water-Supply Paper 771, p. 189
Below Miamisburg	2722	2541	257000	51	Miami Conservancy Dist. Tech. Rep., Part VIII
Hamilton	3672	3491	352000	60	Miami Conservancy Dist. Tech. Rep., Part VIII
Venice	3790	3609	370000	62	Miami Conservancy Dist. Tech. Rep., Part VIII
Miami	3937	3756	384000	63	Miami Conservancy Dist. Tech. Rep., Part VIII

In determining tne net drainage-areas, the whole area of the Lewistown Dam was deducted from that of the first three stations; thereafter, the area of the Loramie Dam was also deducted. Sherman Woodward suggested using one-half of the drainage-area--such a limitation would decrease all the Myers scale-values one point.

Above Piqua, Ohio, the storage of the Lewistown and Loramie reservoirs (with drainage-areas of 100 and 81 square miles, respectively) had an effect, together with a lighter rainfall over the northern portions of the Miami River catchment, of showing relatively small values on the Myers scale as compared with the stations below Piqua. The Myers per cent rating increases downstream. This may be attributed to the fact that on the previous day much heavier rainfall was experienced on the western portion of the river basin on the headwaters of the large tributaries to the main stream below Dayton. On the day of the flood, March 25, the storm was again heavy over the western portions and discharged much greater unit-runoffs to the main stream at a time when the main river-discharge was high. In this instance, the storm-pattern and the physical characteristics of the watershed interplayed to distort the normal curve of runoff. This occurrence with that of the Republican River emphasizes the fact that flood-potentialities of a river can best be approached by recognizing the independent factors existing in the river-system under consideration. The individual hydrographs should be prepared for the tributaries and routed down the channels in order that the changes in the regimen of the river may be properly accounted for when dams or material channel-changes are proposed. By the same token, historical records may become obsolete for direct application and their significance may not be known until routed through the river under the new or proposed changes.

Another interesting series of maximum floods are presented from the Delaware River and West Branch of Susquehanna River. The data were obtained from the "Floods of March 1936 in Pennsylvania," Division of Hydrography of the Department of Forests and Waters. These values are most consistent.

Delaware River, New York and New Jersey

Location	Drainage-area		Oct. 10-11, 1903		Mar. 12-13, 1936		Mar. 18-19, 1936	
	Gross	Net	Flow	Myers scale	Flow	Myers scale	Flow	Myers scale
	sq mi	sq mi	cfs	o/o	cfs	o/o	cfs	o/o
Port Jervis, N. Y.	3076	2730	155000	30	77500	15	109000	21
Belvidere, N. J.	4540	4194	220000	34	148000	23	179000	28
Riegelsville, N. J.	6340	5994	275000	35	184000	24	209000	27
Trenton, N. J.	6800	6454	Ice-jam	..	198000	25	228000	28

It will be noted that the flow for the Delaware River at Port Jervis is lower in terms of the Myers scale than are the values for the downstream stations. Deductions were made for the drainage-area of 118 square miles above Swinging Bridge Dam on the Mongaup River and for that of 228 square miles above Wallenpaupack Dam at Wilsonville which may be considered as regulated. The total deduction made was 346 square miles. There appears to be some characteristic of the drainage-basin which has been effective to indicate a diminished Myers value at Port Jervis beyond that possible from the regulation offered by the dams. A topographic map of the basin and isohyetal maps of the storms should offer some reasonable account. No doubt the channel- and valley-storage along the zigzag channel alignment of the Delaware, and the long tendril-like tributaries draining glaciated regions may account for partial regulation of stream-flow in this area.

West Branch Susquehanna River, Pennsylvania

Location	Drainage-area	June 1, 1889 flow	Myers scale	Mar. 18, 1936 flow	Myers scale
	sq mi	cfs	o/o	cfs	o/o
Bower	315	32600	18	31500	18
Near Westport	2678	......	..	213000	41
Renova	2975	211000	39	236000	43
Williamsport	5682	252000	33	264000	35
Watsontown	6596	......	..	285000	35

North Branch Susquehanna River, Pennsylvania

Location	Drainage-area	Mar. 18-20, 1936 flow	Myers scale
	sq mi	cfs	o/o
Towanda	7797	188000	21
Wilkes-Barre	9960	232000	23
Danville	11220	250000	24

Susquehanna River

Location	Drainage-area	June 2, 1889 flow	Myers scale	Mar. 19, 1936 flow	Myers scale
	sq mi	cfs	o/o	cfs	o/o
Harrisburg	24000	699000	45	740000	47
Marietta	25990	700000	43	787000	49
McCalls Ferry	26766	......	..	875000	53

The above flood-data are interesting in so far as they reveal the fact of the North Branch of the Susquehanna River having been in the area of low precipitation; this suspicion was verified by an inspection of the rainfall-map. Bower, on the headwaters of the West Branch, was in an area of even less rainfall. This is also revealed in the Myers value. In fact, the peak of the flood-crest which originated in New York State above Towanda and Wilkes-Barre arrived there 14 hours later than the flood-crest which was assembled from the local intense rains between Wilkes-Barre and Danville. This emphasizes the importance of strengthening our knowledge of the storm-patterns with respect to intensity, duration, extent, and migration. We need to know how to properly interpolate and extrapolate the measurements of precipitation which are obtained on the watershed. Similarly, we need to strengthen our knowledge of flood-flow dynamics related to the propagation and configuration-changes induced in the hydrograph of the flood-wave as the flood-crest is flattened and the hydrograph elongated in passing downstream.

The foregoing indicate that the Myers scale is a convenient means of appraising a record for the presence of abnormal conditions in a river basin which will modify the flood-crest discharges within the basin. When such departures are indicated, the engineer will do well to limit his use of the Myers scale to component parts of the watershed in such a manner that he is reasonably assured of the presence of normal conditions as to storm-patterns, topography, etc. He may then route the flow through the system independently cumulating the tributary-flow in hydrographs en route to form the main-channel river-flow.

Soil Conservation Service,
U. S. Department of Agriculture,
Washington, D. C.

AN ANALYSIS OF STREAM-FLOW DATA FOR IOWA

F. T. Mavis and Edward Soucek

Synopsis--Stream-flow data for 21 stations on seven major Iowa rivers tributary to the Mississippi River are summarized in this paper. The total area of the seven major basins is 35,620 square miles and is equal to 64 per cent of the area of the State. Separate drainage-areas range in size from 210 square miles to 13,900 square miles. Periods of continuous record extend from a minimum of seven years to a maximum of 33 years. Duration-curves and flood-frequency curves for each station have been analyzed with the view to generalizing the record (1) in terms of mean daily runoff which has been equalled or exceeded a given percentage of the total days of observations, and (2) in terms of greatest daily flood-flows which have been equalled or exceeded with a given average frequency during the period of record.

The results of the study of mean daily runoff are tabulated. For a given percentage of the total number of days record at each station, namely, 90, 75, 50, and 25 per cent, sketch-maps of the State have been drawn showing lines of equal runoff, in second-feet per square mile, which have been equalled or exceeded during the period of record at each station.

The results of the study of flood-frequencies are detailed in frequency-intensity charts for each station of record and summarized in a nomograph showing a relationship between the frequency of a flood, its greatest daily flow in second-feet, and the area of the drainage-basin. The mean absolute deviation between observed and computed maximum daily flows for a given drainage-area and frequency is about 20 per cent.

Stream-flow records of Iowa--Figure 1 shows stream-gaging stations in Iowa for which there are official stage or stream-flow records. The records of 27 stations in the Mississippi Basin and ten stations in the Missouri Basin have been assembled [see 1 of references at end of paper] by the Iowa State Planning Board in cooperation with the Water-Resources Branch of the United States Geological Survey and the Iowa Institute of Hydraulic Research. Records of stages and stream-flow at stations operated by the United States Geological Survey in cooperation with State agencies are published in current Water-Supply Papers. Official records of stages at stations on the principal rivers of the United States are published annually by the United States Weather Bureau in "Daily river-stages." Similar data at stations operated by the United States Engineer Department are matters of official record.

A hydrologic study of the Ralston Creek Watershed of three square miles has been made cooperatively by the University of Iowa, the Bureau of Agricultural Engineering of the United States Department of Agriculture, and the Geological Survey of the United States Department of the Interior. This study has been continued without interruption since 1924 and the data on rainfall, runoff, ground-water levels, and land-use through 1935 have recently been published [2]. The Ralston Creek investigation is unique in the middle west for length of continuous record for a small rural drainage-area.

Table 1--Summary of flow-duration data for Iowa streams

River	Station	Drainage-area	Records included	Per cent of time exceeded				
				90	75	50	25	10
		sq mi		Flow in cfs per sq. mi.				
Des Moines	Keosauqua	13900	1903-06 1911-33	0.042	0.077	0.18	0.46	0.81
	Ottumwa	13200	1917-30	0.048	0.085	0.17	0.38	0.82
	Tracy	12400	1920-27	0.048	0.088	0.18	0.37	0.72
	Des Moines	6180	1915-27	0.036	0.076	0.20	0.48	0.91
	Boone	5490	1920-27	0.022	0.051	0.13	0.35	0.65
	Kalo	4170	1913-27	0.026	0.055	0.13	0.42	0.90
Raccoon	Van Meter	3410	1915-33	0.032	0.062	0.16	0.40	0.84
Skunk	Augusta	4290	1915-33	0.051	0.096	0.22	0.57	1.34
	Coppock	2890	1913-33	0.052	0.097	0.22	0.54	1.25
	Ames	320	1920-27	0.022	0.056	0.18	0.39	0.77
Squaw Creek	Ames	210	1919-27	0.029	0.081	0.23	0.49	1.05
Iowa	Wapello	12480	1915-33	0.107	0.174	0.32	0.63	0.97
	Iowa City	3230	1903-34	0.065	0.121	0.27	0.57	1.10
	Marshalltown	1500	1915-27	0.060	0.113	0.25	0.57	1.15
Cedar	Cedar Rapids	6640	1903-33	0.117	0.170	0.29	0.58	1.06
	Janesville	1660	1905-06 1915-27	0.108	0.151	0.26	0.49	0.96
Shellrock	Clarksville	1660	1915-27	0.066	0.108	0.19	0.41	0.86
Wapsipinicon	Stone City	1310	1903-13	0.091	0.137	0.26	0.59	1.20
Maquoketa	Maquoketa	1550	1913-33	0.219	0.271	0.39	0.65	1.11
Turkey	Garber	1530	1913-16 1919-30[a]	0.144	0.190	0.31	0.54	1.10
Upper Iowa	Decorah	560	1913-14 1919-27	0.112	0.155	0.27	0.50	0.99

[a] No record for 1928.

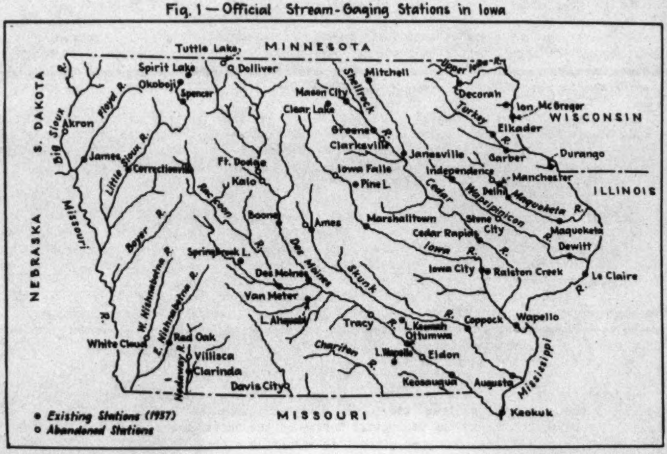


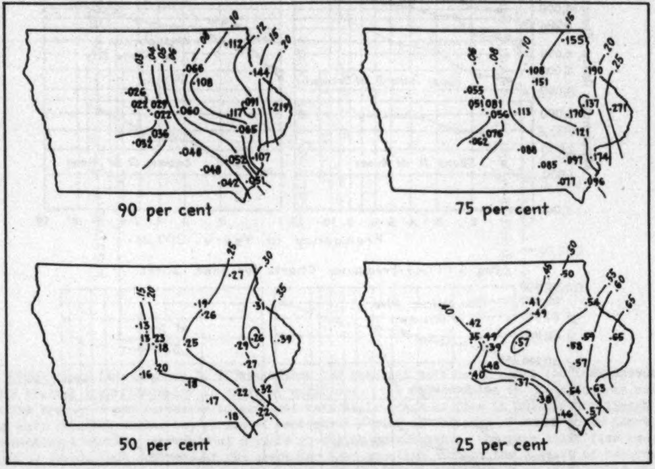
Fig. 1 — Official Stream-Gaging Stations in Iowa

MINNESOTA
S. DAKOTA
NEBRASKA
MISSOURI
WISCONSIN
ILLINOIS
Tuttle Lake
Spirit Lake
Dolliver
Okoboji
Spencer
Big Sioux R.
Floyd R.
Akron
James
Little Sioux R.
Correctionville
Missouri R.
Boyer R.
W. Nishnabotna R.
E. Nishnabotna R.
Nodaway R.
White Cloud
Red Oak
Villisca
Clarinda
Davis City
Ft. Dodge
Kalo
Raccoon R.
Boone
Springbrook L.
Des Moines
Van Meter
L. Ahquabi
Ames
Des Moines
Mason City
Clear Lake
Shellrock R.
Mitchell
Greene
Clarksville
Janesville
Iowa Falls
Pine L.
Marshalltown
Skunk R.
Tracy
L. Keomah
Ottumwa
Chariton R.
L. Wapello
Eldon
Keosauqua
Augusta
Keokuk
Mississippi R.
Upper Iowa R.
Decorah
Ion
McGregor
Turkey R.
Elkader
Garber
Durango
Independence
Manchester
Delhi
Maquoketa R.
Cedar
Wapsipinicon R.
Stone City
Cedar Rapids
Maquoketa
Dewitt
Iowa R.
Iowa City
Ralston Creek
Le Claire
Coppock
Wapello
Existing Stations (1937)
Abandoned Stations

Scope--This paper is limited to a study of all published flow-data for streams on the easterly slope of Iowa tributary to the Mississippi River excepting the records for Ralston Creek--which are readily available--the records of the Mississippi River itself, and other records of less than seven consecutive years.

The purpose of the paper is to present a composite summary of the records in terms of runoff

Fig. 2—Summary of Flow-Duration Curves for Iowa Streams (Figures denote specific runoff in second-feet per square mile equalled or exceeded percentage of days shown)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90 per cent

75 per cent

50 per cent

25 per cent

Fig. 3—Flood-Frequency Charts for Iowa Rivers

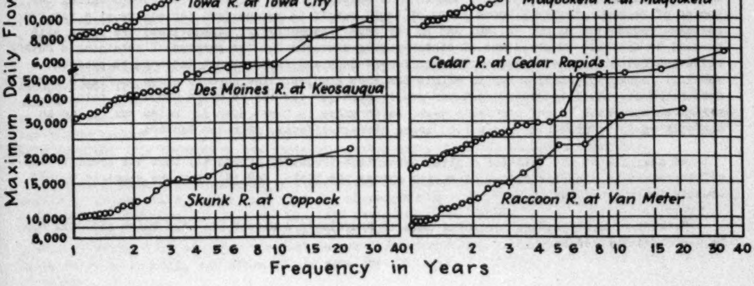


Fig. 4—Flood-Frequency Charts for Iowa Rivers

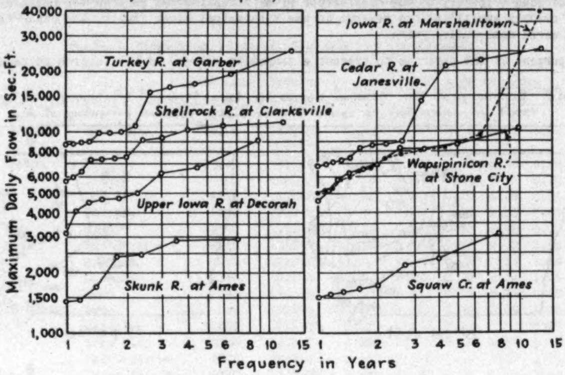
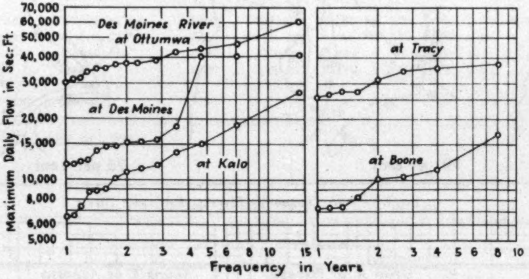


Fig. 5—Flood-Frequency Charts for Iowa Rivers



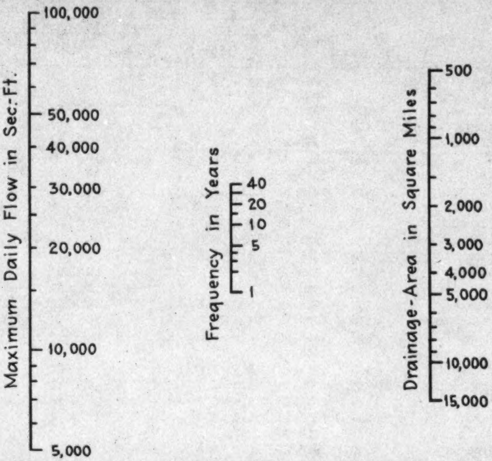
as indicated by duration-curves of mean daily flow, and to present an analysis of mean daily flood-flows in terms of drainage-area and frequency.

Yield of Iowa streams--Table 1 summarizes data obtained from duration-curves showing as abscissas percentages of the total length of record in days and as ordinates the corresponding mean daily flow in second-feet per square mile which had been equalled or exceeded during the period of record. Figure 2 shows lines of equal runoff in second-feet per square mile for percentage-frequencies of 90, 75, 50, and 25 per cent, respectively. These lines are drawn with respect to discrete observations at stream-gaging stations for the purpose of obtaining a rather broad general picture of these particular runoff-data and they are not intended to predict specific runoff for smaller basins within the area studied. The numbers shown on Figure 2 represent rates of runoff in second-feet per square mile for the entire basin above the point of stream-measurement. Along a given stream, differences in these specific rates may be due to differences in rainfall, ground-water flows, storage-effects, or other factors.

An analysis of the data for a given percentage-frequency showed (1) that the specific runoff increased in a northeasterly direction across the State, and (2) that the specific runoff usually increased downstream.

Methods of applying the foregoing data to hydrologic analyses are well known and will not be discussed further here [3].

Fig. 6—Relation between Flood-Flow, Frequency, and Drainage-Area—Iowa Streams



Flood-flows [4]--Figures 3, 4, and 5 show the greatest mean daily flows for independent floods plotted logarithmically in order of magnitude. The charts shown in these Figures represent the frequency and intensity of greatest mean daily rates of flow in independent floods which have occurred during the period of continuous record as follows: For any given chart, representing a continuous record of n years of stream-measurements, the mean daily flow represented by the maximum ordinate of the chart has been equalled once in the n years of record; the flow represented by the ordinate second in order from right to left has been equalled or exceeded twice in two independent floods, or once in (n/2) years on the average; the flow represented by the ordinate m-th in order from right to left has been equalled or exceeded m times in m independent floods, or once in (n/m) years on the average. Some of the floods with frequencies of less than two years are not represented by circles in Figure 3 where the line shown on the chart is so narrowly defined.

Two floods are considered independent if the mean daily discharge in the interval between flood-peaks fell to less than one-half the mean daily discharge corresponding to a frequency of one year for the given station.

While the abscissas of Figures 3, 4, and 5 are designated "frequency in years" for convenience of reference, it is evident that each chart represents a particular record--nothing more. To what extent that record may serve as a basis for estimates of future expectancies must remain a matter for individual judgment and speculation.

Figure 6 shows a nomograph representing a relationship between the maximum daily flow in second-feet, frequency in years, and drainage-area in square miles which was suggested by the charts of Figures 3, 4, and 5. To find, for example, the maximum daily flow to be equalled or exceeded once in ten years for a drainage-area of 3000 square miles, draw a straight line through the points marked 10 on the frequency-scale and 3000 on the drainage-area scale, respectively. This straight line intersects the scale of maximum daily flows at 26,000 second-feet.

Table 2 shows the maximum daily flood-flows for given frequencies interpolated from the charts of Figures 3, 4, and 5, and also the corresponding maximum daily flood-flows computed with the aid of Figure 6. The mean absolute deviation of interpolated and computed rates of flow for these frequencies is approximately 20 per cent. For the frequencies tabulated, the extreme deviations from computed flood-flows are plus 46 per cent for one-year frequency for the Skunk River at Augusta, and minus 57 per cent for five-year frequency for the Des Moines River at Boone.

Table 2--Comparison of interpolated and computed flood-flows for various frequencies

River	Station	Drainage-area in sq. mi.	Records included	Thousand second-feet for frequency									
				1 year		2 years		5 years		10 years		20 years	
				Inter.	Comp.	Inter.	Comp.	Inter.	Comp.	Inter.	Comp.	Inter.	Comp.
Des Moines	Keosauqua	13900	1903-06 1911-35	32	29	42	38	55	55	60	73	86	96
	Ottumwa	13200	1917-30	30	28	37	37	45	53	53	70	..	..
	Tracy	12400	1920-27	26	27	31	35	36	51	..	..	..	..
	Des Moines	6180	1915-27	12	17	15	22	40	32	41	42	..	..
	Boone	5490	1920-27	7.3	16	10	20	13	30	..	..	..	..
	Kalo	4170	1913-27	6.6	13	11	17	16	24	23	33	..	..
Raccoon	Van Meter	3410	1915-35	9.0	11	12	15	22	22	30	28	35	38
Skunk	Augusta	4290	1915-35	19	13	24	17	27	25	31	33	42	44
	Coppock	2890	1913-35	10	10	12	13	17	19	19	25	21	34
	Ames	320	1920-27	1.4	2.3	2.4	3.1	2.9	4.4	..	..	..	..
Squaw Creek	Ames	210	1919-27	1.5	1.8	1.7	2.3	2.6	3.4	..	..	..	..
Iowa	Wapello	12480	1915-35	32	27	37	36	50	51	61	68	64	89
	Iowa City	3230	1903-35	8.0	11	9.7	14	18	21	21	27	25	36
	Marshalltown	1500	1915-27	5.0	6.5	7.0	8.6	8.8	12	22	16	..	..
Cedar	Cedar Rapids	6640	1903-35	17	18	23	23	30	33	52	45	57	59
	Janesville	1660	1905-06 1915-27	6.8	7.0	8.6	9.3	22	13	24	18	..	..
Shellrock	Clarksville	1660	1915-27	5.6	7.0	7.5	9.3	10	13	11	18	..	..
Wapsipinicon	Stone City	1310	1903-13	4.6	6.0	6.9	7.9	8.8	11	10	15	..	..
Maquoketa	Maquoketa	1550	1913-35	8.4	6.7	11	8.8	18	13	19	17	21	22
Turkey	Garber	1530	1913-16 1919-30[a]	8.6	6.6	10	8.8	18	13	23	17	..	..
Upper Iowa	Decorah	560	1913-14 1919-27	3.2	3.4	4.6	4.5	7.0	6.5	..	..	..	..

[a] No record for 1928.

Conclusions--A well-defined pattern of stream-flow and flood-characteristics is apparent from this analysis of flow-data for streams on the easterly slope of Iowa. The records of specific run-off and flood-flows for 21 drainage-basins conform to this pattern despite differences in size of basin, physical characteristics [5], and length of record. No one can say, however, to what extent the data and analyses of relatively short records may be used as a basis for estimating future occurrences on these and other watersheds in the State.

The authors feel that the data will be helpful in the study of hydrologic problems similar to those of the greater part of Iowa and that the methods used in the analysis may reveal patterns of runoff-characteristics for other regions.

References

[1] Stream-flow records of Iowa, 1873-1932, Iowa State Planning Board, Ames, Iowa, 1935.

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PROGRESS-REPORT ON INVESTIGATIONS OF THE RELATION BETWEEN RAINFALL AND STREAM-FLOW

Richmond T. Zoch

In the field of hydrology an immense amount of work has been done and published on the relation between precipitation and stream-flow. This work is of great value although nearly all of it has been descriptive, observational, or empirical.

The history of science shows that the greatest progress in understanding natural phenomena, and hence in predicting their occurrence with accuracy, is attained only after it is possible to express the many relations of such phenomena in a precise mathematical form. Approximate results frequently can be obtained while our understanding of natural phenomena is imperfect and cannot be expressed in terms of mathematical relations; but in the present state of human knowledge, the greatest success is obtained only after natural phenomena can be described by means of mathematics.

It was with this fact in mind, and at the suggestion of the late Montrose W. Hayes, that the writer undertook, several years ago, the task of reducing the relation between rainfall and the subsequent stream-flow to a precise mathematical form. Two articles have already been published on this subject (Mon. Weath. Rev., v. 62, pp. 315-322, and v. 64, pp. 105-121). The third article of this series will appear in an early issue of the Monthly Weather Review.

It seems, and it is hoped that this indication will be altogether correct, that when this series of articles is completed the prediction of stream-flow from rainfall will be on a more firm and sound basis than any other geophysical problem, with the possible exception of the prediction of tides.

In this progress-report it is proposed first to review briefly the underlying assumption upon which the first two articles of the series are based, and secondly to point out certain facts which these articles have revealed.

Those familiar with the development of mathematical physics will realize that in applying mathematics to natural phenomena it is usually essential to make simplifying assumptions to keep the early treatment tractable, but of such nature as not to destroy the usefulness of the results. For this reason many simple assumptions are made in the first article. The various assumptions made there, as well as those made later from time to time, are of two very different types. In the first type are the special assumptions, of which may be mentioned the assumptions that the drainage-area is rectangular, the rate of rainfall is constant, the velocity of the water is constant, there is no evaporation after the rain stops, and the capacity of the soil from place to place within the drainage-area is constant. These special assumptions will be removed one by one as the series of articles continues; they are made solely in order to have the early treatment tractable. In the second type are fundamental assumptions.

The first fundamental assumption is that the rate of runoff at any given time is directly and linearly proportional to the amount of water remaining with the soil at that time. This was the only fundamental assumption in the first paper and, moreover, there were no fundamental assumptions in the second paper. Other fundamental assumptions will be made in the later articles. These fundamental assumptions are made not in order to have the mathematical treatment tractable but because exact observations of the relation postulated have not been made in Nature; for this reason different or more exact laws concerning these relations have not been proven.

Summing up: Special assumptions are made in order to have the early treatment tractable and they will be removed as the theory is developed; fundamental assumptions are made because of the lack of precise observations in Nature.

It is clear that stream-flow is due both to surface-runoff (that is, from water remaining upon the soil) and also to ground-water flow (that is, from water which infiltrates or soaks into the soil). The expression "water remaining with the soil" used in the first fundamental assumption, as well as other places in these articles, means both the water remaining upon the soil and the water which soaks into the soil.

When only surface-runoff is considered, an assumption different from that used in the first paper, namely, that the rate of runoff is proportional to the three-halves power of the depth remaining upon the soil, might yield a closer approximation. At least such is indicated by Torricelli's Law and, while this law neglects friction, it will be instructive to derive an equation on this new fundamental assumption and compare it with the equation given on page 318 of the first paper.

We have the equation

$$\int_0^t Ardt - \int_0^t zdt = \varphi(t)$$

Torricelli's Law states that $v = \sqrt{h}\,\sqrt{2g}$, where v is the velocity of the water and h is the depth (upon the soil here). Clearly $\varphi(t)$, the volume of water remaining upon the soil, equals Ah and z, the volume of rate of runoff, is directly proportional to hv. Hence put $z = c\,h^{3/2}$. On making these substitutions and differentiating we get

$$Ardt - c\,h^{3/2}dt = Adh$$

On integrating this differential equation and recalling that $h = 0$ when $t = 0$ we get

$$t = (A^{2/3}/3c^{2/3}r^{1/3})\Big\{\log[(r - ch^{3/2}/A)/(r^{1/3} - c^{1/3}h^{1/2}/A^{1/3})^3] +$$

$$2\sqrt{3}\,\big(\text{arc tan}\,(\sqrt{3}/3) - \text{arc tan}\,\sqrt{3}/3\,[1 + 2c^{1/3}h^{1/2}/r^{1/3}A^{1/3}]\big)\Big\}$$

This equation is much more formidable to handle than the one, $-(t/c) = \log\,(Ar - z)$, given on page 318 of the first paper. Although this new fundamental assumption gives rise to equations of greater complexity, this will not hinder the attempt to express stream-flow as a function of rainfall. If the equations already given do not express stream-flow with sufficient accuracy, then all that is required is the derivation of corresponding equations from a slightly different fundamental assumption. If necessary, the mathematics can be developed in order to handle the resulting equations.

Turning now to the results that have been accomplished, the first paper gives two runoff-equations and five discharge-equations. The discharge-equations apply for different ranges of time to the case of a rectangular drainage-area. A formula for the time of the crest and another for the maximum discharge is also given in the first paper.

In the second paper five discharge-equations applying to the same ranges of time respectively as those appearing in the first paper are developed. These discharge-equations apply to a drainage-area of any shape whatever such as is encountered in Nature.

It is worth emphasizing that, while the main purpose of obtaining formulae was to enable the United States Weather Bureau to forecast flood-crests on small streams more accurately, the discharge-equations derived serve to reproduce the complete hydrograph from a given rain in its entirety from the time the rain begins till the effect of this rain on the stream-flow becomes negligible. Figure 5 in the second article is an example of such a hydrograph.

In the second paper it is pointed out that a single rain of uniform rate of rainfall can cause a double flood-crest only when the concentration time exceeds the duration of the rain; even in this case such a rain can cause a double crest only if the drainage-area is relatively narrow in its middle portion. Many other important conclusions were pointed out in the second article and will continue to be made as the series is continued.

U. S. Weather Bureau,
Washington, D. C.

DISCUSSION

C. S. JARVIS--Did I correctly understand the speaker's statement to the effect that he had assumed a straight-line relation between water-content of the soil and runoff-volume?

R. T. ZOCH--You heard correctly; that is one of the assumptions which I made, having nothing in my experience to the contrary at that time.

C. S. JARVIS--My experience and observation have been quite contrary to such an assumption. If there is any relationship between volume of runoff and soil moisture-content, I should think it would be an inverse or reciprocal relationship; thus, their sum, together with the evaporation, transpiration, and surface-detention, represents the total rainfall.

I know some fields and pastures capable of disposing of rainfall as it comes, thus yielding only negligible amounts of runoff, and others as impervious as well-kept clay tennis-courts, where the water-content varies but little and the runoff represents practically all of the rainfall.

My worries as a householder, watchful of leaks that occasionally develop in the roof, have made me keenly aware of the precipitation-depths, but not usually through measurement of leakage through defective roof and damaged ceiling. If the roof were sufficiently perforated, its sievelike action would place the entire rainfall in the basement, with no runoff down the gutters. From such extreme examples, it becomes apparent that no consistent lineal relationship should be assumed between soil moisture-content and runoff-volume.

The optimism of the author is to be admired even though his hopes may never be fulfilled to the extent of reducing runoff to as determinate a basis as any other geophysical phenomenon except tidal action. It can be readily granted that such a goal might be achieved for a given set of arbitrary assumptions; but the probability of realizing all the assumed conditions during the phenomena of rainfall and runoff is remote, to say the least. Even when we deal with so-called limiting conditions, factors, and coefficients, we are occasionally impressed by the large factor of safety, uncertainty, or ignorance--whichever may be the correct term.

R. T. ZOCH--Apparently there is no factor in the formula to represent effluent-seepage or ground-water runoff. As this is a principal source of stream-flow in normal and low stages, the formula is apparently applicable only for flood-stages.

In reply to the discussion of this paper, it is believed that the papers in the Monthly Weather Review clearly state all assumptions, and hence indicate exactly what is being neglected. The remaining papers will of course remove many of the restrictions in those already published.

THE ANTICIPATED EFFECTS OF THE FLOOD-CONTROL AND WATER-CONSERVATION RESERVOIRS OF THE MUSKINGUM WATERSHED CONSERVANCY DISTRICT ON THE LOW FLOW OF THE STREAMS OF THE WATERSHED

Waldo E. Smith

In the hills of southeastern Ohio, marking the most southeasterly advance of the continental ice-sheet, lies the watershed of the Muskingum River comprising about 8000 square miles or roughly one-fifth of the area of the State. The northerly and westerly streams forming this complex drainage-system rise in rolling glaciated terrain and in general their channels have quite steep gradients. The easterly tributaries rise in the unglaciated portion of the watershed in a region with much more rugged topography, but with valley-floors that are comparatively flat, thus making for sluggish meandering streams into which the runoff from the hills rushes. Originally a high percentage of this area was forest-covered, but much of the land has been denuded to secure the available timber and to make available lands for agricultural and other pursuits, so that now only a small percentage is covered with timber.

Under construction on this watershed at the present time are 14 large flood-control dams, eleven of which will also form permanent lakes for water-conservation and recreational purposes (see Fig. 1). Considering the flood-control aspect only, this project is not unlike the one completed a decade and a half ago on the watershed of the Miami River in western Ohio, except that the Muskingum Drainage-Area is over twice the size of the Miami Drainage-Area and for this reason the problem of flood-control is much more complex. Due to this complexity in large measure, gate-controlled rather than fixed outlets are used for flood-control in all cases excepting one, to provide the necessary flexibility in operation. The shaded area on Figure 1, comprising 4267 square miles or 53 per cent of the total watershed or 62 per cent of the area above Zanesville, will be under control. This paper, however, concerns itself not with the flood-control aspects, but the water-conservation and low-flow aspects of this project.

The conservation-storage in the case of this project is at all times under the present plan to be kept separate from the flood-control storage-capacity. In other words, up to a certain elevation the storage is to be for purposes of conservation, and above this elevation is to be for flood-control purposes, so that there is no dual utilization of storage-space contemplated under the present plan. The advantage of combining the two purposes in one reservoir is economy of construction and site. In some cases the storage-capacity was more than doubled over that required for flood-control, without increasing the cost of the dam more than a few per cent.

At three of the dams (Bolivar, Mohicanville, and Mohawk) there are conditions that preclude the development of any storage in excess of the flood-control requirements, so these three will store water only temporarily at flood-times. At two others (Dover and Beach City), there is only very limited storage-space in excess of the flood-control needs, and the small amount of conservation-storage in these two reservoirs will be primarily for recreational purposes.

At the other nine sites the conservation-storage could of course be used entirely to create permanent lakes for recreational purposes alone, or it could be used entirely to regulate the flow during dry seasons but, more likely, it will be used for a reasonable combination of these two divergent interests. At the outset there will probably be little demand for water for municipal or industrial purposes, but as time goes on, demands in this connection are likely to increase and it is possible that at such future time considerable revenue will be derived from the sale of water without damaging materially the recreational aspects of the project. Under circumstances likely to prevail upon completion of the control-project, however, the main interest will be to maintain a reasonable dry-weather flow in the channels downstream from the pool without causing objectionable draw-down in the reservoirs.

Thus the studies, carried on in connection with the conservation-storage, had in mind, first, the operation necessary to maintain a reasonable minimum flow, and second, the possible future maximum demand that can be made upon these pools without seriously damaging their recreational aspects. In the shallower reservoirs the maximum draw-down can probably be not more than three feet but in the deeper reservoirs it may run as nigh as five feet. On the basis of these two arbitrary figures as maximum draw-down, studies for maximum uniform draw-off during dry seasons were made. The effects of the low-flow outlet works without using the draw-off gates were also investigated for several of the reservoirs of the first group mentioned below.

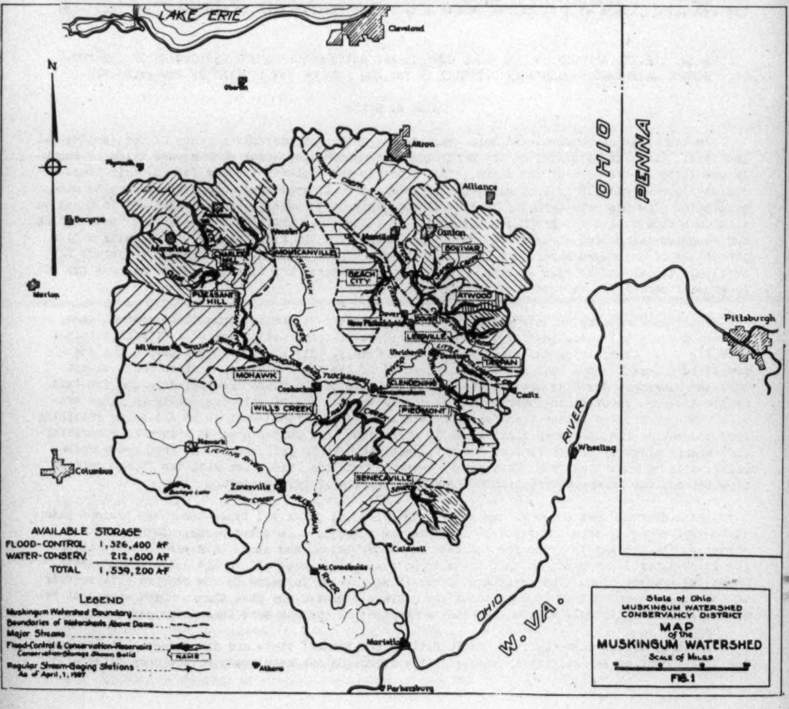
LAKE ERIE
Cleveland
N
Akron
Alliance
OHIO
PENNA
Bucyrus
Marion
Mansfield
Wooster
Massillon
Canton
CHARLES MILL
MOHICANVILLE
PLEASANT HILL
BEACH CITY
BOLIVAR
ATWOOD
Dover
New Philadelphia
DOVER
LEESVILLE
Uhrichsville
Dennison
TAPPAN
Cadiz
Mt. Vernon
MOHAWK
Coshocton
CLENDENING
WILLS CREEK
PIEDMONT
Newark
LICKING RIVER
Columbus
Zanesville
Cambridge
SENECAVILLE
RIVER
Wheeling
Pittsburgh
Caldwell
Mc Connelsville
RIVER
OHIO
W. VA.
Marietta
Athens
Parkersburg
AVAILABLE STORAGE
FLOOD-CONTROL 1,326,400 AF
WATER-CONSERV. 212,800 AF
TOTAL 1,539,200 AF
LEGEND
Muskingum Watershed Boundary
Boundaries of Watersheds Above Dams
Major Streams
Flood-Control & Conservation-Reservoirs
Conservation-Storage Shown Solid
NAME
Regular Stream-Gaging Stations
As of April, 1, 1937
State of Ohio
MUSKINGUM WATERSHED
CONSERVANCY DISTRICT
MAP
of the
MUSKINGUM WATERSHED
Scale of Miles

FIG. 1

Table 1 is an attempt to put the conservation-pools into their natural grouping and to give other pertinent information on the reservoirs and the tentative conclusions of these studies. In the first group of six, which lie on the eastern tributaries of the watershed, are those having the greatest lake-area and conservation-storage in relation to area of their watersheds. These have been grouped in order of decreasing ratio of lake-area to watershed-area, which ratio it will be noted varies from 5.17 per cent to 3.25 per cent. These have marked similarity in regard to geology, except the Atwood Reservoir whose drainage-area is in the region of the most advanced position of the continental ice-sheet. From the standpoint of dam- and control-structures these all have marked similarity also, excepting the Senecaville Reservoir. The others have gate-controlled outlets located at low elevation, which have the joint purpose of affording flood-regulation and the drainage of the conservation-pool quite completely. Approximately at the elevation of the conservation-pool are placed two siphons having throats four feet by one foot, the purpose of which is the regulating of low flow without adjustment of the gates. These siphons operate as weirs under normal dry-weather conditions but during protracted drought, or after a draw-down of 0.75 feet below the nominal level of pool, water ceases to flow through them, and to provide outflow one of the gates must be opened slightly. The Senecaville Dam has two gates at low elevation also, but for the purpose of draining the reservoir and regulating low flow only. It has a weir-crest of considerable length located 1.2 feet below the nominal conservation-pool level, which crest acts as the sill for the Taintor gates which when closed provide the necessary flood-control storage. No siphons are provided. To draw off water below the weir-crest, it is necessary to open slightly one of the two gates located at low elevation.

Table 1--Natural and regulated low-flow data and other pertinent information on the reservoirs of the Muskingum Watershed having conservation-storage

Reservoir	Drainage-area sq. miles	Conservation-pool area, acres	(Lake-area/drainage-area) x 100	Conservation-pool volume, acre-feet	Conservation-pool volume, inches on dr.-area	Volume in 3-foot draw-down, acre-feet	Volume in 5-foot draw-down, acre-feet	Average depth conservation-pool, feet	Yearly minimum monthly flow,[a] natural	Yearly minimum daily flow[a]				Type of conservation spillway	Years of record
										Natural	No draw-down	3-foot draw-down	5-foot draw-down		
Group I															
Tappan	71	2350	5.17	35100	9.27	4800	8900	14.9	1-8	0-5	0-5	4-47	11-81	Siphons	8
Senecaville	121	3550	4.59	43500	6.74	9800	15350	12.3	1-10	0-5	0-5	11-57	21-65	Weir	8
Piedmont	84	2270	4.23	33600	7.50	4800	8700	14.4	1-8	0-6	0-7	4-28	11-41	Siphons	8
Clendening	70	1800	4.01	27900	7.47	3500	6550	15.5	1-14	Inc	Inc	4-29	9-54	Siphons	13
Atwood	70	1540	3.43	23600	6.32	3100	5900	15.3	8-26	Inc	Inc	13-49	22-64	Siphons	13
Leesville	48	1000	3.25	19500	7.62	2000	3800	19.5	0-6	Inc	Inc	5-30	8-37	Siphons	15
Group II															
Charles Mill	216	1350	0.98	7400	0.64	3300	4600	5.48	13-65	Inc	Inc	20-85	26-90	Weir	6
Pleasant Hill	199	850	0.67	13500	1.27	2000	3300	15.9	28-60	Inc	Inc	43-89	46-93	Weir	13
Beach City	300	420	0.22	1700	0.11	840	1300	4.05	15-37	Inc	Inc	22-49	25-57	Weir	6
Wills Creek	844	900	0.17	6000	0.13	2300	3300	6.67	6-72	Inc	Inc	12-107	19-122	Weir	8
Dover	1397	350	0.04	1000	0.014	670	850	2.86	181-415	Inc	Inc	192-474	195-477	Gate sills	13

Conclusions and recommendations for initial operation

Group I

Tappan--1 to 2 cfs with maximum draw-down 1.9 to 2.2 feet
Senecaville--1 to 2 cfs with maximum draw-down 2.4 feet
Piedmont--1 to 2 cfs with maximum draw-down 1.9 to 2.2 feet
Clendening--1 to 2 cfs with maximum draw-down 1.95 to 2.3 feet
Atwood--3 to 5 cfs with maximum draw-down 1 foot
Leesville--1 to 2 cfs with maximum draw-down 1.6 to 1.9 feet

Group II

Charles Mill--No draw-down
Pleasant Hill--No draw-down
Beach City--No draw-down
Wills Creek--Probably no draw-down
Dover--No draw-down

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[a] Upper limit does not include the minimum flow for wet summers; all flows are in terms of cubic feet per second; "Inc" indicates that studies at present are incomplete in the detail indicated.

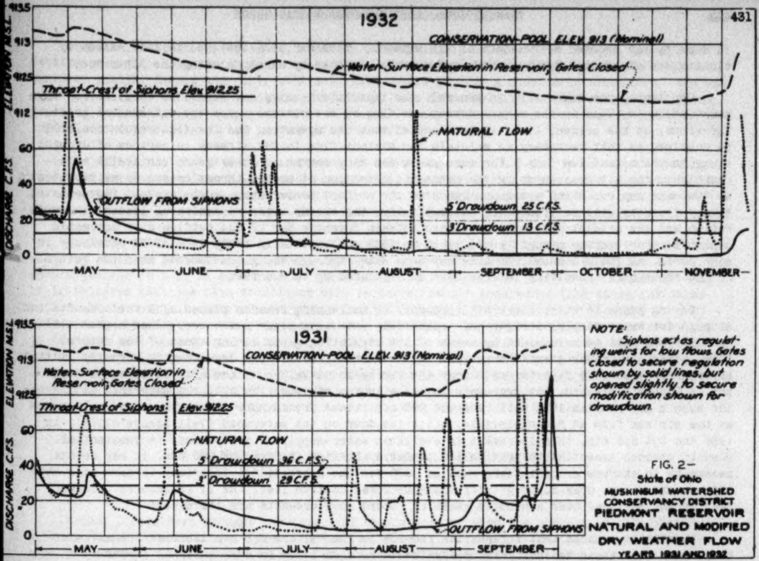
On these streams, because of the large ratio of water-surface to drainage-area and because of the large effect of evaporation from the water-surface and of the normally low dry-weather flow from this unglaciated area, low-flow conditions without the operation of gates were of special interest.

The other group of five have relatively small ratios of lake-area to drainage-area. This is in all cases less than one per cent, and evaporation is not of as much importance. Furthermore, all of these watersheds are substantially larger than those of the first group and, with the exception of that of Wills Creek, are located in glaciated regions from which the low flow in terms of cfs per square mile is substantially greater than from the unglaciated part of the watershed. It is likely that, with the possible exception of Wills Creek Reservoir, no draw-down will be necessary to maintain a reasonable dry-weather flow. The chief effect of these conservation-pools will be the tendency to iron out the usual variations in flow resulting from the occasional showers that occur during the dry season. Even this effect in the case of the Dover Reservoir, in which the pool is so small that it is out of the banks only at a few points, is negligible. Three of the dams of this group, namely, Beach City, Charles Mill, and Wills Creek, are very similar in their outlet structure, in that the low flow is controlled by a weir immediately downstream from which is the flood-control structure including the gates. The Pleasant Hill Dam is a modification of this, in that here there is no normal gate-control of the flood and the weir-crest for low flow is the lower edge of the orifice affording automatic flood-control. In this case, gates for draining or drawing off are provided at low elevation in the conservation-pool. In this case of the Dover Dam, there are three batteries of six gates, the sills of the uppermost of which act as a control-weir for low flow.

The most detailed studies were made of Piedmont Reservoir falling in the middle of Group I. Not only were studies made on a monthly or tri-monthly basis using three feet and five feet of draw-down to determine the uniform outflow that could be maintained with the available storage, but also a day-by-day study was made of the conditions that would result, with no draw-down other than that provided by the automatic regulation by the siphons and the losses due to evaporation, to determine whether or not flow could be maintained without opening gates during dry seasons. Results of these latter studies for 1931 and 1932 are shown on Figure 2. During 1931 precipitation was approximately normal, and during 1932 was subnormal, especially during the summer months. On both of these hydrographs, the elimination of the peaks in flow due to summer freshets is very marked. In the case of 1931, a normal year, the low flow with the conservation-pool at no time would have dropped below the minimum that occurred under natural conditions for that summer. The protracted dry season of 1932, however, and the high evaporation during that period would have resulted in the drop in the water-surface below the throat-crest of the siphon resulting in the period of zero-flow which under natural conditions was much shorter. Our studies indicate that under natural conditions the flow was less than one cfs for approximately 45 days, but under the conditions existing after the completion of this dam, zero-flow would have occurred for 42 days with less than one cfs for 60 days.

In this region the driest period of record for the hundred odd years for which records are available was 1930. Had this Reservoir been in existence at that time and had there been no drawing off of water through gates, the surface of the pool would have dropped to a point 1.6 feet below the nominal pool-level or 0.85 feet below the throat of the siphons. The loss of the 0.85 feet is directly due to evaporation. For each 0.3 feet additional draw-down roughly one cfs of flow could have been maintained, with three feet of draw-down resulting in an available uniform outflow of about four cfs. However, without draw-off, had this conservation-pool been in existence, there would have been 250 days extending into 1931 during which there would have been no flow immediately below the Dam. Under natural conditions there were 65 days during which the natural flow was less than one cfs. It can be seen, therefore, that the automatic regulation afforded by the siphons discharging as weirs under low flow improves conditions in normal and wet years, but that for drought-years the condition of low flow in the stream is aggravated and extended, requiring draw-off to maintain flow. However, the maintenance of a flow of one cfs, which is substantially greater than the minimum flow for the same period, means a draw-down of but 0.3 feet additional to the inroads made by evaporation. Figure 3 shows the Rippl diagrams for the years investigated for this Reservoir, excepting that the very wet year of 1935 is omitted. Note that these tend to show that protracted droughts, such as that of 1930, are well under way by the early part of July--the beginning of the driest part of the year--and revised estimates of available flow may then be made which for ordinary drought-conditions will probably increase earlier conservative estimates substantially.

The conditions found to hold for the Piedmont Reservoir appear with variation in values to hold for all of the reservoirs of Group I, excepting Senecaville which, because of the weir-arrangement, has tendency to draw down the water to the weir-crest level much more rapidly than



NOTE: Siphons act as regulating weirs for low flows. Gates closed to secure regulation shown by solid lines, but opened slightly to secure modification shown for drawdown.

FIG. 2—
State of Ohio
MUSKINGUM WATERSHED
CONSERVANCY DISTRICT
PIEDMONT RESERVOIR
NATURAL AND MODIFIED
DRY WEATHER FLOW
YEARS 1931 AND 1932

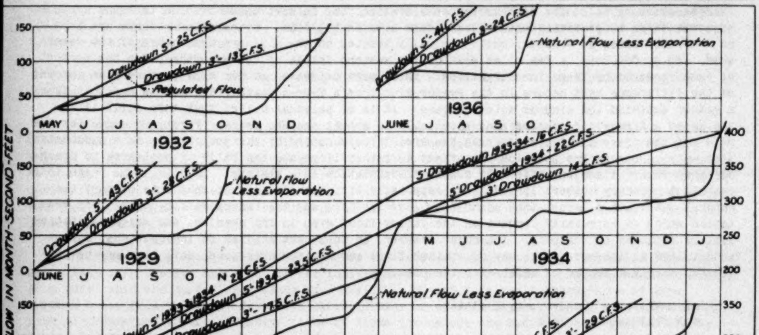


FIG. 3—
State of Ohio
MUSKINGUM WATERSHED
CONSERVANCY DISTRICT
PIEDMONT RESERVOIR
RIPPL DIAGRAMS
REGULATION BY DRAWDOWN
FIGURE 3

is done by the shorter weir-length of the siphons. This can be alleviated to some extent by closing one of the two Taintor gates and somewhat further by nearly closing the other one.

Concerning the reservoirs in general, the immediate demands, as mentioned earlier, for any substantial increase in the normal summer low flow of the streams below the dam are not great. Therefore, at the present time, it is expected that the operation for low-flow regulation will be confined to that necessary to maintain the minimum flow in the streams in periods of drought equal to the normal low flow. For some years and many months of other years, this will be accomplished for all reservoirs by the automatic operation of siphon-throat crests or weir-controls, as the case may be, which are installed near the nominal conservation-pool levels. The peaks of summer freshets will be ironed off automatically, the excess water replenishing losses by evaporation and the gradual decrease in storage between freshets due to the outflow over automatic controls. For extreme drought-years, such as 1932 and especially 1930, it will be necessary in some cases, as Table 1 shows, to draw out some water through the gates located near the bottom of the reservoirs, resulting in draw-down as indicated up to 2.4 feet.

During years to come, there will probably be increasing demands placed upon the conservation-storage for water-supply, irrigation, industrial, and steam-power plant use. Then higher minimum outflows will be maintained by means of the regulating gates during times of low natural flow. This will cause greater draw-down in the reservoirs. If the draw-down is normally limited to from three to five feet in order that the recreational values of the artificial lakes will not be unduly decreased, the aggregate increase in the minimum flow over the watershed as a whole for such a dry year as 1932 will be about 200 cfs, these preliminary studies indicate. Inasmuch as the minimum flow at McConnelsville, quite low down on the watershed (7411 square miles), in 1930 was but 218 cfs, this increment in available water-supply in dry periods is substantial. When it becomes essential to provide a dependable all-time increase of 200 cfs, it may become necessary in extreme drought-years such as 1930 for the recreational interests to make some sacrifices and accept draw-downs greater than the three to five feet. Be it remembered, however, that on the basis of over a hundred years of record such droughts are infrequent.

It should be added that stream-flow records in general are not available at the sites of these dams and it was necessary to use synthetic records based in some cases on stream-flow records above or below the site under consideration, but in most cases records taken on streams adjacent to or in proximity with the drainage-area in question. Evaporation-records are kept on a monthly basis at Wooster, quite centrally located on the northern headwaters of the watershed, and at Columbus, a few miles west of the western fringe of the watershed, for the period of years covered by these investigations. These were decreased 40 per cent to take some account of the difference that occurs in the evaporation from a Type-A Weather Bureau pan and that from a rather extended and sinuous water-surface. It is my personal belief that this still allows too large a figure for evaporation, especially in normal and wet years. First, no deduction was made for the present water-surface on the area to be occupied by the pool. This is a substantial item only in reservoirs in which the stream is rather large and the ratio of pool-area to drainage-area is small and the effect of reservoir-regulation is a minimum. Thus in those cases this oversight probably matters little. But especially this method does not take into account the natural evaporation-losses that occur from land-surfaces and the transpiration-losses from vegetation which is especially verdant on the valley-floor even in dry seasons, and which vegetation will be replaced by the pool. Inasmuch, however, as these are studies to indicate what may be anticipated or desired in the way of minimum flows and maximum draw-down, this item may be considered merely a factor of safety for the present.

Muskingum Watershed Conservancy District,
New Philadelphia, Ohio

DISCUSSION

C. S. JARVIS--There is much value in the comprehensive descriptions, charts, and tabulated data contributed by the author concerning the regulating effect of the proposed reservoirs on stream-flow within the Muskingum Conservancy District. Because of the emphasis accorded the periods of drought, the reader is likely to underestimate the beneficial influence of these storage-projects during years of average or above-normal precipitation. Furthermore, it may be reasonably assumed that during years of drought the strict limitations on draw-down, and perhaps on live storage-levels as well, may be modified considerably in the interest of water-conservation and beneficial use. The author has indicated the reasonable probability of such liberalized regulations, particularly with respect to increased draw-down for the purpose of augmenting flow in summer.

One item, hitherto unmentioned, seems to add measurably to effective storage, perhaps offsetting evaporation-losses in whole or in part. The lateral infiltration into fairly open-textured glacial debris and other bank-materials should provide a considerable volume of storage outside the reservoir-basin contours. Naturally, this increase will be most noticeable during years of subnormal water-supply, when it might well account for nearly doubling the natural minimum flow, particularly during periods of pronounced draw-down.

The writer has observed many instances of substantial seeps and fairly permanent springs that have developed adjacent to storage-reservoirs, or to irrigated tracts; and similar results have accrued from spreading of flood-waters over coarse debris cones to increase underground storage.

WALDO E. SMITH--The comments of Dr. Jarvis are well taken. It is recognized by the author that the paper as presented by no means represents a completed study of low-flow conditions. It should perhaps be well to elaborate on the closing statement of the paper which intimates that it is believed that low-flow conditions will be better rather than worse than those indicated by this study and that uncertain favorable factors (of which lateral infiltration may be one) were considered simply on the order of a factor of safety. Attention should further be called to the fact that the reservoirs of Group I in which low-flow conditions are the most adverse, lie on unglaciated areas and there is little open-textured material for the storage of water. It is characteristic of the banks of these reservoirs to be rather dense in texture, being largely material in situ resulting from the decay of shales and fine-textured sandstone, and will probably offer a minimum in effect as far as increasing minimum flow is concerned.

A GRAPHIC METHOD OF ROUTING FLOODS THROUGH RESERVOIRS

R. S. Goodridge

Recent floods have brought the people of this nation to view the problem of flood-control with increased interest. To effect the desired control, it is axiomatic that the runoff-rates must be reduced. This may be accomplished through two major approaches which may supplement the existing capacity in a watershed for (1) infiltration or absorption of rainfall into the soil-cover and profile, when possible, and (2) detention and desynchronization of flood wave-crests by the use of surface-storage.

This paper deals with the latter phase limited to a method of routing floods through the surface-storage of reservoirs.

The method was initiated by efforts of the late C. B. Gibbons in behalf of the Los Angeles County Flood-Control District of California in 1929. Subsequent modifications were used by Messrs. R. E. Copeland, M. F. Burke, and E. S. Fuller until in 1934 the graphic procedure presented here was developed. The writer was privileged to have been associated with the District during this period and feels that the utility of the method recommends it for publication to the end that those engaged in flood-routing problems may consider the use of this solution among the others available.

The controversy which often develops over the relative values of large and small dams suggests that quantitative appraisal of the individual merits of proposed structures would be aided if a more rapid and more direct means were available by which to route hydrographs of flow through a dam or a series of dams. The effectiveness of storage may be expressed in terms of the reduction obtained in the excessive rates of flows throughout the hydrograph as well as at the crest. The modified hydrograph may be incorporated with tributary flow below and other surface-, channel-, or pool-storage, treated independently, to form a new hydrograph for downstream works.

Several procedures, mathematical, semi-graphic, and graphic, have been used by engineers to solve routing problems, such as those listed in the attached references and published by H. K. Palmer, C. C. Jacobs, Professor Harold A. Thomas, R. E. Horton, Raymond A. Hill, Professor R. D. Goodrich, Professor H. K. Barrows, G. R. Clemens, C. J. Posey, the Army Engineer School of Belvoir relating to the Muskingum Flood-Control Project, and others. None of the above methods use the time-rate or inflow hydrograph-curve as the base for directly constructing the outflow-curve thereon, which is accomplished by this method.

For illustration, a simple case of flow over a spillway is shown in Figure 1 with hypothetical curves of inflow, storage, and discharge, as follows:

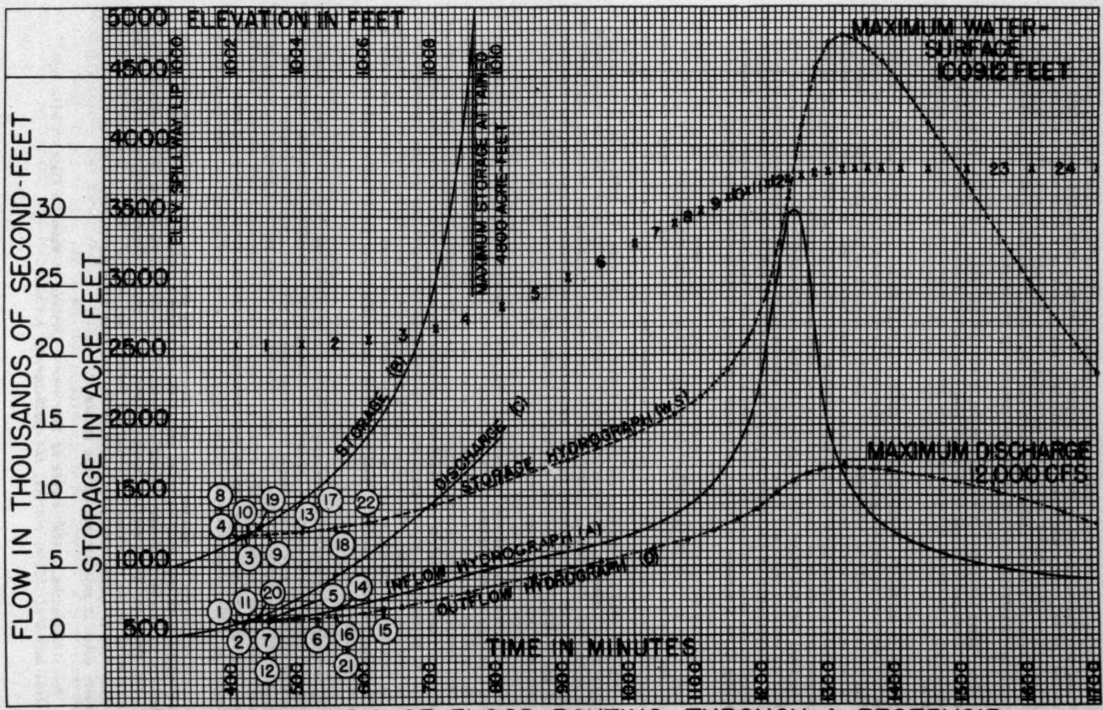


FIG. 1—GRAPHIC ANALYSIS OF FLOOD-ROUTING THROUGH A RESERVOIR

Item	Coordinates Abscissa	vs	Coordinates Ordinate	Units		
Inflow-hydrograph (A)	Time		Rate	Minutes	vs	cfs
Storage-curve (B)	Stage		Volume	Feet	vs	acre-feet
Outflow-discharge (C)	Stage		Rate	Feet	vs	cfs

On Figure 1 is illustrated the method of arranging the curves for the hypothetical case at hand.

The discharge-curve (C) is shown employing the same scale of flow in cubic feet per second as is used for the inflow-hydrograph. This is plotted against the stage or elevation in feet which served for the storage-curve (B). The discharge-curve may show the combined values of the discharge-capacities for as complex a system as may be desired.

On the storage-curve may be placed the elevations of the various ports as valves, gates, and tunnels, and also the spillways as reference-data to describe the outlet associated with the discharge-capacity curve.

The above curves are shown on Figure 1 and serve as a basis for beginning the solution of the outflow-hydrograph (O) and the attendant storage-hydrograph (WS). The water-surface is obtained for any time by referring the storage cumulated to the storage-elevation curve.

On Figure 2 is shown the data of Figure 1 for the first two steps (time-intervals) of the graphical analysis with enlarged scales to aid the reader in following the operations performed.

The method of operation of a proposed or existing reservoir will govern the selection of the initial water-stage or pool-level. In the case illustrated on Figure 1, the reservoir is assumed to be full and discharging through the spillway at a rate equal to the inflow into the pool. This assumption requires that the determination of the surface-elevation at which this state of equilibrium will obtain be established first. This is found from the stage-discharge curve (C) for the initial outflow, points 1 and 2.

The storage corresponding to this stage and discharge-rate is shown by reference to the storage-curve (B), point 3, since the discharge-curve is referred to the same elevation-scale. Point 3 establishes point 4 at the 400-minute ordinate, the initial storage at which equilibrium is established between the inflow and the discharge in accordance with the assumed operating conditions.

The graphic analysis, which may now be started, is a "cut-and-try" method of approximating the solution of outflow for successively chosen periods of time.

The fundamental theory follows: The desired mean outflow for any period representing an increment of time, Δt, is a function of the mean or average inflow, the average operative head, and the storage-increment during the time period selected.

The initial storage will be increased depending upon whether or not the inflow-rate exceeds the discharge-rate developed by the storage-head. In Figure 1 the system is in equilibrium at the minimum or initial flow of the hydrograph; therefore, with progressively increasing flow the storage-curve will rise to a maximum at a point where the inflow-and outflow-hydrographs intersect. Thereafter the outlets discharge more water than is received by virtue of the head attained through the previously cumulated storage.

The mean inflow of the 100-minute interval, 400-500 minutes, is approximated at a point slightly above the lower third of the offset, on the mid-ordinate of the time-interval, to the chord drawn between the terminal ordinates of the time-interval segment and the arc or boundary of the inflow-hydrograph.

Having established the mean inflow of the first time-interval, point 5, determine the time required for flow to cumulate a like linear-scale distance of the flow and the storage. From Figure 1 it is seen that 5000 units of flow in cubic feet per second equal 500 units of storage in acre-feet or ten units of flow per unit of storage. It follows that the time in minutes required for 10 cfs to cumulate one acre-foot equals $43{,}560/(10 \times 60) = 72.6$ minutes.

This time-interval represents a fixed relation between the scales of the rate of flow and storage. To illustrate, we may consider a rectangle of ordinate Q and abscissa T on the rising stage as shown below on Figure 3.

The diagonal OS_2 represents a slope showing the time-rate-change of flow and the corresponding rate of cumulation of storage.

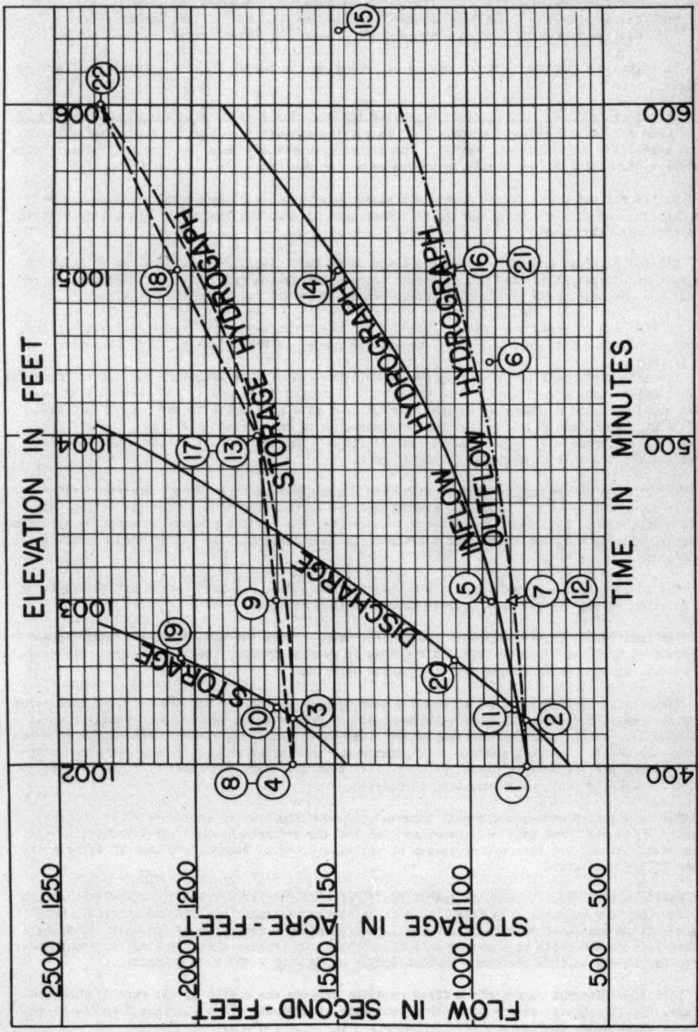


FIG. 2—ENLARGED SCALE TO ILLUSTRATE GRAPHIC PROCEDURE

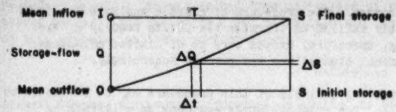


FIG. 3—GRAPH OF FLOW-STORAGE CONVERSION

Storage = Rate of storage-flow x time

$S = QT$

Differentiating we have $dS/dt = Q$. Then, for any storage-flow, the difference between mean inflow and mean outflow, the slope drawn for the increment of storage-flow as an ordinate on the conversion-time t as the abscissa, will represent correctly the rate-change of storage for any period for which the flow is considered the average.

This time-flow-conversion determination is the key to the solution, for it permits the graphic cumulation of storage accruing from the difference between mean inflow and mean outflow for any selected time-interval. It is possible, therefore, to vary the time-intervals or the length of segments of the hydrograph in order that long intervals may be used when the rate-change in the inflow is small; and diminishing time-intervals, when the rate-change is rapid. By thus varying the length of the time-interval, the form of the outflow-hydrograph may be defined as closely as desired. The use of longer intervals naturally increases the speed of the solution, but does not reflect the character of the outflow-hydrograph as accurately.

With the flow-storage conversion-time established, the graphical analysis may begin.

The mean inflow for the first interval, 400-500 minutes, has been taken at point 5. This point is then transferred horizontally to the right a scale-distance equal to the conversion-time, 72.6 minutes, and appears as point 6. Point 7 is now estimated as a possible mean outflow. The slope from point 6 to 7 (hereafter designated 6-7) represents the diagonal of Figure 3 or the rate-change of storage for interval 1. By use of appropriate triangles, this slope is transferred to point 4, the initial water-surface, and extended to the mid-ordinate of the interval, point 9, to show average storage in acre-feet during interval 1.

Since this average storage corresponds to an average elevation which in turn must be in agreement with the estimated mean outflow-value, it must be confirmed by checking through the storage- and discharge-curves, points 10 and 11, and 12. Should 12 fail to coincide with 7, a new estimate must be made and the above procedure repeated. When the outflow-rate is confirmed, the storage-rate slope is produced from 4 through 9 to 13, a fair representation of the storage-hydrograph during the interval. A true representation may be derived, if desired, by drawing a smooth curve through successive terminal points of the storage attained at successive time-intervals.

The second interval chosen is the period between 500-600 minutes. The time-interval bounds may be conveniently indicated by using x's, as shown, consecutively numbered. The mean flow of interval 2 is represented by point 14. The time-interval of 72.6 minutes is set off to the right and referenced as point 15. A mean outflow-discharge for interval 2 is estimated at point 16. The conversion-slope 15-16 is transferred to point 13 (17) produced to mid-ordinate at point 18. Confirmation of this estimated storage is secured by checking back through the storage-curve at point 19, thence down to the discharge-curve at point 20, and thence to the right to the mid-ordinate of interval 2, point 21, where the estimated discharge, point 16, is confirmed when point 21 coincides with point 16. Point 18 may then be extended to point 22 on slope 15-16, a slope identical to slope 13 (17) - 18. This operation completes interval 2.

The graphical study is continued as above, by successive time-intervals. On Figure 1, all time-intervals are marked. The mean inflows of the successive intervals, when transferred by the linear distance of the conversion-time, are witnessed by the time-interval numbers associated, as reference- or witness-number designations save time by minimizing the possibility of errors in referring to points. The author uses a dashed line as symbolic of the storage hydrograph and the dot-and-dash for the outflow-discharge.

It is suggested that accurate results may be obtained by the use of a pair of bow-dividers with center control; one may be set to the linear scale-measure of the conversion time-interval and thereafter used to set off the period for each successive interval throughout the study, and the other bow-divider is used to transfer points both horizontally and vertically by referencing the distance from a point to a parallel of the coordinate-paper. This method is adaptable to drafting-machine use without material loss of accuracy. Triangles should be used for rate-change transfers of storage and outflow-increments. It is an advantage to have the reference-triangle weighted down. This leaves both hands free to operate pencil-and-bow divider with one hand and the free triangle with the other. Adjustments of the position of the weighted reference-triangle are readily made by easing and shifting a corner. The procedure of graphic analysis is rapid, especially when the draftsman is sufficiently skilled to transfer the points readily by eye. The inherent errors tend to be compensating; therefore, excess care is of limited advantage. The draftsman may quickly appraise his personal limitations and proceed accordingly.

The measure of the accuracy of the graphical analysis of this procedure may be reflected by a consideration of results shown on Figure 1. The original study was done on a 10-inch by 15-inch sheet. A check on the work was obtained by planimetering (A), the acre-feet of water placed in storage, by the flow in excess of the outflow to the point of maximum discharge, and (B), also the flow in acre-feet of the spillway-discharge in excess of the inflow. (A) was found to equal about 3557 acre-feet and (B) to equal 2415 acre-feet. Since the initial storage is seen to be about 1220 acre-feet, the addition of 3557 acre-feet totals 4777 acre-feet at the maximum stage or pool-level attained. This is shown on Figure 1 as 4800 acre-feet. Similarly, the storage at the 1700th minute is seen to be about 2370 acre-feet, to which may be added (B), 2415 acre-feet, to total 4785 acre-feet. The discrepancy in totals is (4785 - 4777) = 8, or an error of about 0.2 per cent. In another comparison of the foregoing quantities, we may balance inflow and outflow; (3557 - 2415) = 1142 acre-feet against the increase in storage shown as (2370 - 1220) = 1150 acre-feet, again obtaining 8 to give an error of about one per cent. In other words, the accuracy of the graphical method is adequate for the demand.

In the design of a dam, use may be made of a number of outlet- and spillway-arrangements by drawing the corresponding elevation-discharge curves on the same sheet. The graphical study then makes possible the direct comparison of the relative operating results which may be obtained for an official-plan flood. The designer may make any necessary adjustments of the proportions involved to secure the best design for the need.

This method offers advantages of flexibility in design and in appraising various methods of operating existing structures with a system of both manual and fixed outlets. In certain problems of existing dams, the slide-rule of Professor C. J. Posey will expedite the routing of a series of flood-flows with similar operating schedules. In general, at least in the handling of the flashy flood-crests of small drainages, the construction of mass-curves is hardly warranted and a direct graphical solution may be used to advantage.

The above method is adaptable for the approximation of channel-storage effects on a hydrograph of flood-flow. The Manning formula is used for obtaining the variation of flow-capacity of the channel (assuming uniform flow). Thus a stage-discharge curve is obtained. The channel cross-section data serves to give a stage-storage curve for a specific reach of the channel. The notation of Figure 1 is maintained with the exception that "elevation in feet" is made to read "stage in feet." The storage-curve is shown as a time-function of the inflow-hydrograph. The graphic analysis at the flood-crest makes use of the rising storage to the point of the maximum stage. Since the channel-storage effects a reduction in the rate of the flow it is necessary to refer the discharge-rate to the appropriate storage-scale. The configuration-change in the hydrograph resulting from applying the same procedure as used for a reservoir is in the proper direction--both flattened and elongated, thus simulating nature. Since such analysis considered storage only, and not the propagation of the segments of the hydrograph, use is made of Seddon's law to indicate the configuration-change resulting therefrom in the reach of channel under consideration. A graphic solution of Seddon's law

$$\text{Wave-velocity} = (Q_2 - Q_1)/(A_2 - A_1)$$

gives the velocity of the flood-wave and, for the reach, time in minutes for the propagation of the flood-wave from the upstream-station to the downstream-station.

This channel-storage approach was used subsequently by E. S. Fuller to incorporate a correction to the configuration of hydrographs developed from rainfall storm-patterns for the total storage utilized in the assembly-channels.

The combination of the above approaches serves to resolve by approximation the independent effects of channel-storage and wave-velocity as they tend to modify the configuration of the flood-wave. Channel-storage reduces the crest-flow and elongates the flood-wave; wave-velocity determines the propagation time for the reach. The flood-wave problem is indeterminate and much more information is desired, particularly from hydraulic-laboratory approaches in which the underlying physical phenomena may be attacked through control of the independent variables.

The routing of flow through reservoirs is a relatively simple matter; the routing of the flow from reservoir to reservoir is a complex problem. The best contribution to date is that of

Professor Harold A. Thomas in his "The hydraulics of flood-movements in rivers," originally published in 1934, and for which a second edition was issued in 1936. This appeared as a bulletin of the Carnegie Institute of Technology.

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DISCUSSION

C. S. JARVIS--Methods of routing floods have been in practical use for many years, and consequently the designs of several important projects took account of the results derived from such analyses.

One notable contribution was from the Committee on Reservoirs, appointed by the Chief of Engineers, United States Army, with Colonel William Kelly as Chairman. The report of this Committee as rendered at the October, 1927, meeting of the American Society of Civil Engineers at Columbus, Ohio, presented the conclusions reached concerning the probable influence of Miami Conservancy District and other flood-control reservoirs, either storage or detention, if they had been in operation during outstanding storms and floods of the Ohio and Mississippi valleys. The conclusions of the Committee as published (Trans. Amer. Soc. Civil Eng., v. 93, pp. 724-736, 1929) were necessarily based on broad assumptions, approximations, and adaptations of flood-routing methods then in vogue, in order to accomplish the herculean task within the prescribed time-limits. In that brief analysis, the effects of valley-storage and other moderating influences were admittedly neglected. As a result, the estimated effects of reservoirs on Mississippi River flood-heights were measured in inches or fractions thereof, either positive or negative; that is, the chances of aggravating flood-heights seemed to be nearly equal to those of reducing them, and generally insignificant in magnitude.

Now that an orderly, logical, graphic procedure has been developed which automatically reduces the physical data and basic assumptions to composite-record form, it would be interesting and profitable to make an independent approach to the same problem, to evaluate the probable reduction or increase of Ohio and Mississippi River flood-crests resulting from outstanding storms, with reservoirs operated primarily to serve one or more of the local interests, such as regulation of power, navigation, water-supply, or flood. Many investigators in the field of hydrology, including the writer, are confident that the results and conclusions would be radically different from those originally published and particularly opposed to the next to the last paragraph of that report, so nearly the antithesis of recent trends, policies, and approved projects, as follows:

"To conclude, the prospects for reservoirs as a part of a Mississippi flood-project are not very good. One after another of the possibilities have 'washed out' till practically nothing is left, except certain relatively small reservoirs of the Upper Mississippi and certain reservoirs in the Mississippi Valley proper or at the mouths of the principal tributaries and even they do not look very promising."

NATURAL STREAM CHANNEL-STORAGE

(Second Paper)

Robert E. Horton

Introduction-Synopsis--The runoff-rate and runoff-graph at an outlet or point on the stream-channel are not the same as the rate and graph of direct surface-runoff from the area upstream from the outlet, owing to the fact that the direct surface-runoff is modified by channel-storage.

The author's first paper on this subject (Trans. Amer. Geophys. Union, 1936, pp. 406-415) gives a method of determining the volume of stream channel-storage during recession of a stream-rise. It is shown that the volume and outflow-rates from channel-storage, exclusive of ground-water, are related through the equations

$$q_c = K_c h^R \tag{1}$$

$$S_c = K_z h^S \tag{2}$$

Then

$$h = (q_c/K_c)^{1/R} = (S_c/K_z)^{1/S} \tag{3}$$

and

$$q_c = K_c(S_c/K_z)^{R/S} = K_{sc}S_c^{M} \tag{4}$$

where $M = R/S$. Also,

$$S_c = (q_c/K_{sc})^{1/M} = K_{cs}q_c^{1/M} \tag{5}$$

where

$$1/M = S/R \tag{6}$$

$$K_{sc} = K_c/K_z^{M} \tag{7}$$

and

$$K_{cs} = K_z/K_c^{1/M} \tag{8}$$

where S_c = volume of channel-storage in cubic feet, h = stream-stage in feet above the level of zero-outflow at the control-section, and q_c = outflow from channel-storage, excluding ground-water flow, in cubic feet per second.

(The following changes in notation have been made:

First paper		Second paper
K_S'	becomes	K_z in $S_c = K_z h^S$
q_s	becomes	q_c in $q_c = K_{sc}S_c^M$
K_c	becomes	K_{sc} in $q_c = K_{sc}S_c^M$

The last member of equation (5), p. 407 of first paper, should be stricken out, and in the following line $M = (R-S)$ should be $M = R/S$. The following corrections of statements appearing in the first paper are necessary: Page 407--It is subsequently shown that, during recession, channel outflow-rate does not return to equality with the initial ground-water inflow-rate in a finite time if the ground-water inflow is constant, but does return to equality therewith in a finite time if, as is usually the case, the ground-water inflow-rate decreases. Page 414--The channel-storage outflow-rate relation for receding stages, derived by the method given in the first paper, cannot be applied to rising stream-stages.)

Equations of the same type as (1), (2), (4), and (5) can also be applied to the total flow and storage, including ground-water.

In the first paper the results of analyses of stream-rises were given showing the values of the exponent M and the coefficient K_{sc}. In the present paper it is shown that the observed values of M above referred to are in good agreement with the values to be expected from hydraulic considerations.

Data are given, derived from analyses of stream-rises, showing the volume of channel-storage during recession when the channel outflow-rate is one csm and it is shown that these volumes are related both to the size of the drainage-basin and the stream-density. It is also shown that the channel-storage-outflow rate-curve for a complete stream-rise, including both rising and receding stages, has usually the form of a hysteresis loop. It is shown that channel-storage behaves nearly the same as if the entire volume of channel-storage was concentrated in a single detention-reservoir having the same characteristics as to volume and area as the channel-storage and the same outflow-capacity. This makes it possible to treat analytically the subject of outflow-graphs as modulated by channel-storage. The effect of channel-storage in reducing flood-crests and regulating outflow is complicated in most cases by the presence of ground-water inflow and outflow. Expressions are derived for channel-outflow for both the rising and receding sides of the channel outflow-graph, and examples are given showing the effect of a constant inflow of ground-water. The results given in the paper have an important bearing on the validity of certain assumptions made in connection with the unit-graph method and in other lines of hydrologic research.

The exponents R and S--The total storage-volume in a given stream-channel is essentially a pyramid of constant altitude equal to the stream-length. The total volume of channel-storage for a given stream-stage at the outlet or point of measurement is the sum of the volumes of the pyramids corresponding to all of the streams in the drainage-net. The value of the exponent S in the stage-storage equation $S_c = K_2 h^S$ is determined by the weighted average form of the channel section: For a rectangular section, $S = 1$; for a parabolic section, $S = 3/2$; for a triangular section, $S = 2$.

The value of the exponent R in the stage-discharge equation as applied to the total flow, $q = K_q h^R$, is determined by the form of the cross-section of the control-section, which governs the stage h. If the slope and roughness of the channel between the gaging-section and the control-section do not vary with the stage, then, from the Manning formula,

$$q = (1.486/n)\ Ar^{2/3}\ \sqrt{S}$$

where A = section-area in square feet at stage h and r is the hydraulic radius.

For a wide rectangular section, $r = h$, A varies as h, and $R = 5/3$; for a parabolic section, r varies approximately as h, A varies as $h^{3/2}$, and $R = 13/6$, approximately; for a triangular section, r varies as h, A varies as h^2, and $R = 8/3$.

The control-point at any gaging-section or outlet, as it is here called, is either at or a little distance downstream from the gaging-section. The stage h is the depth above the level of zero-discharge at the control-section and may be less than the depth at the point of measurement. The slope at the control may vary with the stage. If it increases with h, the exponent R is increased, and vice versa.

The form of the average channel-section which controls volume of channel-storage, and the form of the channel-section at the control, and which controls discharge-rate, may not be the same but they are usually similar figures. If the slope at the control is invariant and the section-forms controlling R and S are the same, there will be the following relations between R and S:

Section	R (discharge)	S (storage)	(R/S)	(S/R)	(S-R)
Rectangular	5/3	1	5/3	3/5	-2/3
Parabolic	13/6	3/2	13/9	9/13	-2/3
Triangular	8/3	2	4/3	3/4	-2/3

Departures from these values may occur. Those of R result from variations in slope. In Detroit River, for example, R is close to unity. Variations in the exponent S may result from outflow on to flood-plains and from extension of the length of the stream-channels containing channel-storage in case of partial-area floods which produce back-water storage in some of the tributary streams.

In the above table (S-R) is always negative and has the constant value -2/3. It is possible that in some cases (S-R) may be positive, since the effect of departures from normal conditions is likely to reduce R and increase S. Also the ratio (S/R) is likely to exceed the values 0.60 to 0.75 rather than to fall below these values. The following values of the ratio (S/R), derived from actual stream-rises, were given in the first paper.

Thirty-three floods on Ralston Creek, Iowa, showed (S/R) ranging from 0.60 to 0.80 in 25 cases, from 0.80 to 1.00 in five cases, and greater than one in three cases.

Thirty-four floods on eight larger streams showed (S/R) less than 0.50 in one case, from 0.50 to 0.60 in three cases, from 0.60 to 0.80 in 16 cases, from 0.80 to 1.00 in eight cases, from 1.00 to 1.20 in four cases, and 1.20 in two cases.

It is interesting to note that, while these values were derived from data from which ground-water flow was eliminated, they are in good agreement with the values to be expected when the equation $S_c = K_{cs}q_c{}^{1/M}$ is used and ground-water flow is included in q. This suggests that the presence of a constant rate of inflow of q_g of ground-water and a nearly constant rate of outflow of ground-water may be neglected in deriving the equation of the recession-side of a stream-rise as affected by channel-storage.

Volume of channel-storage--The equation $q_c = K_{sc}S_c{}^M$ gives

$$S_c = (q_c/K_{sc})^{1/M} = \sqrt[M]{1/K_{sc}}\, q_c{}^{1/M} \qquad (9)$$

Values of K_{sc} and M are easily derived from the recession-side of the hydrograph by the method given in the first paper. Equation (9) applies strictly to recession-stages after direct surface-runoff ends, that is, beyond the point of inflection on the outflow-graph, and hence only to stages somewhat below the maximum. If A is the drainage-area in square miles, then making $q_c = A$ and writing $S_c/A = B_c$, equation (9) gives

$$K_{cs} = (1/A)\sqrt[M]{1/K_{sc}} \qquad (10)$$

The quantity K_{cs} is the volume of channel-storage in cubic feet per square mile at a stage where the rate of discharge of channel-storage is one csm. This equation furnishes a basis for determining both the relative volumes of channel-storage provided by the drainage-nets of different streams and the variation in volume of channel-storage in the same stream in different recession-periods. Volumes of channel-storage expressed in cubic feet per square mile by equation (10) can be converted into inches depth on drainage-basin by the equations

$$S_{c1} = 0.4305\ S_c/1{,}000{,}000\ A, \quad K_{cs} = 0.4305\ B_c/1{,}000{,}000 \qquad (11)$$

In the first paper, volumes of channel-storage in cfs-days or cfs-hours were given for numerous streams and stream-rises. Table 1 contains additional information. Column 7 of Table 1 shows the volume of channel-storage in cubic feet per square mile at a recession-stage where the outflow-rate is one csm. Some of the rises listed in Table 1 were partial-area floods, that is, the rain was not sufficiently intense to produce rainfall excess and surface-runoff from part of the area. The effective flood-area, where determined, is given in column 4. It will be noted in particular that, for the same stream, the unit-storage varies over a considerable range in different stream-rises. This variation is also related to the character of the rise.

Table 2 contains similar data for a large number of stream-rises on the drainage-basin of Ralston Creek.

The base channel-storage K_{cs} is an important physiographic index. It summarizes in a single-valued constant the drainage-development or dendrition of a drainage-basin. For equal dendrition a large basin with the same climate, soil, and topography usually contains about the same length per square mile of first-order or finger-tip tributaries and a greater length and volume of larger stream-channels than are contained in a small basin, so that K_{cs} should increase with size of basin. This increase is marked for small basins but becomes relatively small when large basins are compared.

TABLE 1 – CHANNEL-STORAGE CHARACTERISTICS FROM STREAM-FLOW GRAPHS IN W.S.P. #772

Stream	Dr.-Area Sq. Mi.	Date of Flood-Crest	Effective Flood-Area	Crest-Discharge on Effective Area C.S.M.	M	Unit-Storage[(b)] K_{cs} Cu.Ft./Sq.Mi.
(1)	(2)	(3)	(4)	(5)	(6)	(7)
French Broad River	4450	Aug.4, 1921	100%	8.53	0.573	301,000
at Dandridge, Tenn.		Apr.7, 1922	54% upper	7.90	0.716	245,000
		Sept.23, 1923	75% •	6.63	0.682	369,000
		May 2, 1932	100%	6.51	0.660	223,500
		Average			0.660	284,620
Red River	39400	June 18, 1930	(a)	(a)	0.510	(a)
at Denison, Texas		Dec.7, 1930	(a)	(a)	0.573	(a)
		Jan.7, 1932	(a)	(a)	0.660	(a)
		Sept.5, 1932	(a)	(a)	0.773	(a)
		Average			0.629	
Susquehanna River	7770	Oct.7, 1918	55% lower	6.78	0.730	200,000
at Towanda, Pa.		Apr.6, 1923	(a)	(a)	0.666	93,300
		Oct.1, 1924	100%	16.71	0.860	106,000
		Nov.24, 1924	(a)	(a)	0.760	190,000
		Oct.4, 1929	100%	3.60	0.786	138,000
		Oct.7, 1932	80% lower	8.85	0.810	122,000
		Average			0.769	141,550
Delaware River	3070	Oct.31, 1917	100%	29.6	0.793	98,500
at Port Jervis, N.Y.		Oct.7, 1918	•	5.15	0.946	143,500
		Apr.30, 1923	•	8.8	0.773	115,200
		Oct.1, 1924	•	31.0	0.800	76,000
		Oct.5, 1927	•	5.4	0.786	135,000
		Sept.5, 1933	•	7.7	1.185	67,500
		Average			0.880	106,000
Embarrass River	1540	Sept.17, 1920	100%	0.45	1.130	127,500
at Ste. Marie, Ill.		June 14, 1929	(a)	(a)	0.965	123,500
		Average			1.048	125,500
Skunk River	4290	July 25, 1924	(a)	(a)	0.963	159,500
at Augusta, Iowa		June 4, 1927	(a)	(a)	1.152	135,100
		Sept.2, 1931	(a)	(a)	0.893	121,000
		Average			1.003	138,530
Muskingum River	5980	June 6, 1927	100%	4.00	0.726	162,000
at Dresden, Ohio.		June 27, 1927	(a)	(a)	0.820	195,000
		July 4, 1927	(a)	(a)	1.316	105,600
		Aug.21, 1932	20% upper	2.25	1.098	162,000
		July 3, 1933	90% lower	1.80	1.250	172,000
		Average			1.042	159,230
Wabash River	3830	Aug.5, 1929	18% upper	9.05	0.816	176,000
at Logansport, Ind.		Aug.16, 1929	78% mid	2.74	0.650	190,000
		Average			0.733	183,000

(a) Not determined (b) Unit-storage is channel-storage in Cu.Ft. per Sq.Mi. when outflow-rate is 1 C.S.M.

Table 2--Ralston Creek channel-storage

Date (1)	M (2)	K_{cs}, cubic feet per square mile[a] (3)
June 3, 1925	0.667	4740
July 6, 1925	1.050	10000
August 12, 1925	0.683	2870
September 8, 1925	1.000	4610
June 12, 1926	0.810	1372
June 14, 1926	0.750	1908
September 19, 1926	0.833	3200
September 22, 1926	0.793	1020
May 8, 1927	0.680	567
May 18, 1927	0.946	2390
May 23, 1927	0.640	469
May 24, 1927	1.163	6290
June 20, 1927	0.689	461
October 2, 1927	0.703	509
October 6, 1927	0.686	894
May 18, 1928	0.759	992
June 24, 1928	0.650	513
July 4, 1928	0.600	794
July 19, 1928	0.651	706
August 23, 1928	0.769	1062
June 11, 1929	0.829	1044
June 13, 1929	0.883	1322
July 1, 1929	0.776	885
August 2, 1929	0.777	960
June 22, 1930	0.670	485
June 14, 1930	0.700	537
July 19, 1931	0.680	655
September 21, 1931	0.658	334
September 25, 1931	0.746	820
November 23, 1931	0.639	432
June 17, 1932	0.800	659
July 10, 1932	0.675	311
August 1, 1932	0.763	642
Averages	0.761	1650

[a] Unit-storage is channel-storage in cubic feet per square mile when outflow rate is one csm.

The following are the average values of K_{cs} derived for different drainage-basins:

Drainage-basin	Area, square miles	No. of storms	Average K_{cs}
Ralston Creek, Iowa City, Iowa	3.05	33	1650
Embarrass River, Ste. Marie, Illinois	1540	2	125500
Delaware River, Port Jervis, New York	3070	6	106000
Wabash River, Logansport, Indiana	3830	2	183000
Skunk River, Augusta, Iowa	4290	3	138500
French Broad River, Dandridge, Tennessee	4450	4	284600
Muskingum River, Dresden, Ohio	5980	5	159320
Susquehanna River, Towanda, Pennsylvania	7770	6	141550

Ralston Creek, with 3.05 square miles, shows a value of $K_{cs} = 1650$ cubic feet per square mile, while all the other streams listed, with drainage-areas exceeding 1000 square miles, show values of K_{cs} exceeding 100,000 cubic feet per square mile. This suggests one of the reasons why unit-flood intensities decrease as size of area increases and it also suggests that the channel-storage constant K_{cs} is one of the factors that should be included in flood-discharge formulas. For the larger basins the Table shows a slight but only a slight tendency for K_{cs} to increase with size of drainage-basin. For the larger basins listed, the effect of size is probably masked owing to the fact that the constant K_{cs} reflects stream-density or length of streams per square mile of area. This is clearly shown by comparing Skunk River (4290 square miles) for which K_{cs} = 138,500, with the French Broad River (4450 square miles) with K_{cs} = 284,600. Skunk River is on the Great Plains. Its drainage-basin is flat agricultural land, with about 32 inches of rainfall and low stream-density. French Broad River is in the southern Appalachian Mountains, has an unusually high stream-density, and over 50 inches of rainfall. Its channel-storage per square mile is more than twice that of Skunk River.

For the larger streams listed, the channel-storage constant K_{cs} is generally between 100,000 and 200,000 cubic feet per square mile, or 0.04 to 0.08 inch of depth on the drainage-area, for a channel outflow-rate of one csm. Channel-storage is greater for rising than for receding stages and increases faster than the stage but usually slower than the discharge at the outlet. On drainage-basins such as the larger ones listed, channel-storage volumes ten, twenty, or even more than twenty times K_{cs} are to be expected at about the crest-interval during major floods. Few floods on such areas exceed 2 to 4 inches of depth of total runoff, so that 25 to 50 per cent of the total flood-volume may easily be required to fill channel-storage. This shows at once the modulating effect of channel-storage in reducing flood-intensity.

Channel-storage behaves like water concentrated in a single reservoir--The equation relating channel-storage and outflow, $q_c = K_{sc}S_c^M$, and its constants for different streams have been derived directly from observed data for receding stages when there is no direct surface-runoff. An equation identical in form would apply under similar conditions to a reservoir concentrated just above the outlet having areas and capacities equal to this channel-storage and with the same curve of relation of stage to outflow. The fact that under these conditions channel-storage behaves like water concentrated in a single reservoir is not altogether easy to explain, especially when one takes into consideration the fact that the channel-storage in a drainage-basin such, for example, as that of the Muskingum or Delaware River, is distributed through several thousand miles of stream-channels and may be interrupted by rapids or even abrupt falls interposed along the course of the stream.

During rising stages a similar situation exists except that, as subsequently shown, the relation of channel-storage to outflow-rate is different. The following general statement appears true. During the passage of a stream-rise, channel-storage in a stream-system of a drainage-basin behaves the same as a single detention-reservoir located at the outlet during rising stages, and behaves the same as a reservoir of somewhat smaller capacity during receding stages.

These results would hardly be expected. In case of a concentrated reservoir there is an instant response in the outflow to any change of inflow, whereas in the case of channel-storage it may require several days for the physical transfer of water from the more remote finger-tip tributaries to the outlet. A complete explanation will not be attempted but the following discussion serves to show the principal reasons for this remarkable fact.

Consider a detention-reservoir with free outlets equal to channel-capacity at the same stages and located at a given point on a stream-channel. If I_1, Q_1, and A_1 are the inflow- and outflow-rates and surface-area of the reservoir, respectively, at a given time t during the passage of a stream-rise, then, applying the storage-equation to this reservoir gives

$$I_1\,dt = Q_1\,dt + A_1\,dh \tag{12}$$

If, now, a second reservoir is placed immediately upstream, with inflow-rate I_2, outflow-rate Q_2, and area A_2 at the same stage as for the first reservoir, then for this reservoir, operating alone and at the time t, the storage-equation gives

$$I_2\,dt = Q_2\,dt + A_2\,dh \tag{13}$$

The two reservoirs may be considered as equivalent to channel-storage in two successive reaches of a stream-channel. If the upper reservoir discharges immediately into the lower reservoir, the inflow to the lower reservoir is $(I_1 - I_2 + Q_2)$ but, from equation (13) $Q_2\,dt = (I_2\,dt - A_2\,dh)$. For this condition the storage-equation gives, for the operation of the lower reservoir

$$(I_1 - I_2)\,dt + I_2\,dt - A_2\,dh = Q\,dt + A_1\,dh \tag{14}$$

from which

$$I_1\ dt = Q\ dt + (A_1 + A_2)\ dh \tag{15}$$

Here Q is the outflow-rate from the lower reservoir.

If the two reservoirs were combined and operated as a single reservoir, with area $(A_1 + A_2)$ and inflow I_1, then from the storage-equation

$$I_1\ dt = Q\ dt + (A_1 + A_2)\ dh \tag{16}$$

This is identical with equation (15) and the outflow-rate at any given time from the single or combined reservoir will be identical with the outflow-rate from the lower reservoir if the two are operated separately, the upper discharging into the lower. This proof can be extended to n successive reservoirs, each equivalent to the channel-storage in the tributary or in a reach of the main stream between two control-points. The proof is therefore general and shows that during the passage of a stream-rise, the entire system of channel-storage in a drainage-basin, although broken up between tributaries and reaches separated by outflow control-points, nevertheless behaves the same as if the entire channel-storage was concentrated in a single reservoir.

This rule is, however, subject to the requirement that no time-lag occurs between discharge from one reach or reservoir and the reflection of its effect in the next reach or reservoir downstream.

There is undoubtedly an element of time-lag in the case of large drainage-basins which modifies the result given somewhat, but much less than might be expected.

If a bathtub is filled with water to overflow-level and a quart of ink is dumped into the end opposite the outflow, the water will instantly rise and overflow although it may take hours for the ink to reach the outlet. What occurs in this case is the transmission of a surge--not primarily the physical transmission of the water. There is, of course, a transfer of water but it is only a differential transfer. The wave or surge retains its form, like an ocean-wave; the water comprising the wave differs at every point in its progress. Failure to understand certain aspects of flood-wave and channel-storage phenomena arises in part from the tendency of most persons to think in terms of actual physical transfer of the water. Surges are generated in the same way and, for the same depth, move at nearly the same velocities in running streams as in still water. In deep, still water the velocity of the surge, in feet per second, is $\sqrt{gd}$, where d is the depth in feet.

Consider a system of stream-channels replaced by a reservoir 1,000,000 feet or roundly 200 miles long, 100 feet wide, and 25 feet deep. In such a reservoir a surge would travel 161 feet per second or roughly 100 miles per hour. The effect of water entering the upper end of the reservoir would be reflected at the outlet in less than two hours. If the actual velocity of hydraulic flow was ten feet per second or six miles per hour--and it is seldom greater in floods in natural rivers--it would require roundly 33 hours for actual physical transfer of water through the length of the reservoir.

Relation of channel-storage for rising and receding stages--There is no simple method of determining precisely the volume of channel-storage during rising stages from the outflow-graph, as can be done for receding stages. Hence for the purpose of illustrating the relation of channel-storage for rising to that for receding stages, a hypothetical case has been used. Figure 1 shows triangular surface-runoff and channel-outflow graphs, each with a total runoff of 0.8 inch. Channel-outflow is assumed to begin one-half hour later than channel-inflow. Actually they should begin simultaneously but, owing to channel-storage effect, the channel outflow-rate is negligible for a short time. The channel-storage line, showing the volume of channel-storage in inches of depth, has been drawn by subtracting the mass channel-outflow from corresponding values of the mass inflow or mass surface-runoff. This line shows a maximum channel-storage at the time of maximum channel outflow of 0.35 inch. This channel-storage reduces the runoff-crest from 0.40 inch per hour, or 256 csm, to 0.265 inch per hour, or 170 csm. Plotted on log paper in terms of channel outflow-rate, as shown by Figure 2, the channel-storage line shows two branches meeting at a point corresponding to the outflow-crest. For rising stages the channel-storage is not accurately represented by a simple power-function but is nearly proportional to the first power of q_c or is nearly in direct proportion to the channel outflow-rate. During receding stages, after surface-runoff ends, the equation of channel-storage is $q_c = 0.39\ S_c^{0.525}$, or the channel-storage varies nearly as the square of the outflow-rate in this instance.

Plotted directly, as shown on Figure 3, the hysteresis-loop resulting from the fact that during rising stages more water is flowing into the channel than is flowing out, and conversely

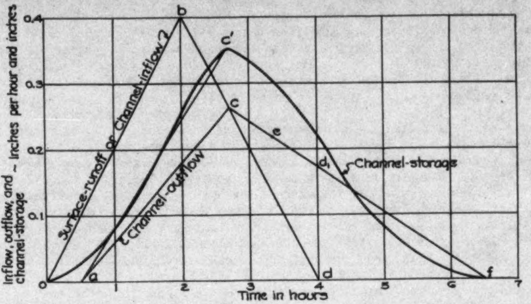

FIG. 1 - CHANNEL-STORAGE DURING A STREAM-RISE

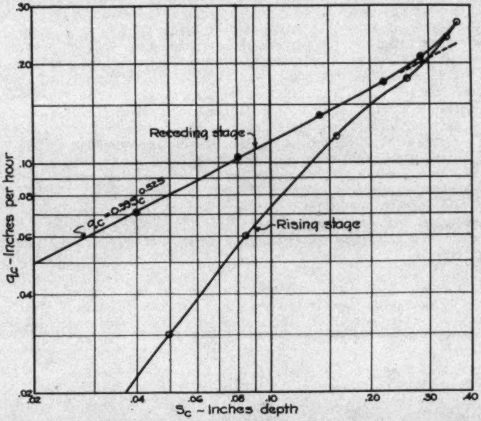

FIG. 2 - LOGARITHMIC PLOTTING, CHANNEL-STORAGE-OUTFLOW-RATE

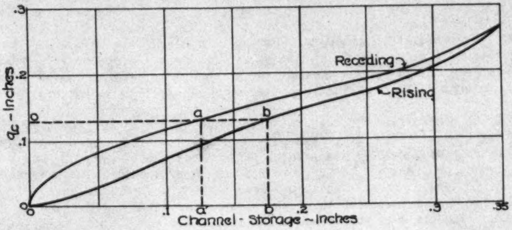

FIG. 3 - HYSTERESIS - LOOP OF CHANNEL-STORAGE

for receding stages, is clearly shown. It may be remarked that this hysteresis-loop is characteristic of this relation between inflow and outflow, and its existence does not depend either on the characteristics of the stream-channel or the relation of stage to outflow. The hysteresis-loop is related to but is not identical with the loop in an open-section rating-curve, sometimes observed, particularly on flat streams, where discharge-measurements made before a flood-crest show higher discharges for the same stage than those made after the crest has passed. The relation of this phenomenon to the channel-storage hysteresis-loop is discussed later.

On Figure 1 a straight line ac' has been drawn and it will be noted that this nearly coincides with the channel-storage curve for rising stages except at the beginning of the rise. No great error would be made if it was assumed in this case that during rising stages the channel-storage increases uniformly with time, from zero to a at the beginning of definite channel-inflow, to its maximum value at c' at the time of the outflow-crest. It can readily be seen that the volume of channel-storage during rising stages would increase directly in proportion to the time for triangular inflow- and outflow-graphs if surface-runoff and channel-outflow began simultaneously. Under these conditions the rates of channel-inflow and channel-outflow at any time t would be K_1t and K_2t and the increment of channel-storage per unit of time at any time t would be $(K_1 - K_2)$ or a constant quantity. The channel-storage at c' is unknown and, as shown by the dotted extension of the line for receding stages on Figure 2, the volume of channel-storage at c' does not coincide with that for receding stages. A close approximation to the channel-storage at the outflow-crest can apparently be obtained by taking off from the storage recession-curve extended, the channel-storage corresponding to the outflow-rate at a point midway between the outflow-crest and the end of channel-inflow (point d, Fig. 1). For usual forms of runoff-graphs the latter is at or near the point of inflection on the recession-side of the outflow-graph. On Figure 1 the outflow surface-runoff ends at d' and the point e is midway between d and c. In this instance the outflow-rate at this point (e, Fig. 1) is 0.222 and the corresponding channel-storage, from the equation $q_c = 0.39\ S_c^{0.525}$, is 0.342 inch, whereas the maximum channel-storage at c' is 0.35 inch. This rule requires further development and refinement but, in conjunction with the nearly linear variation of channel-storage with time during rising stages, it apparently affords a simple approximate basis for correcting the outflow-graph for channel-storage during rising stages, as can be done during receding stages, and so converting an outflow-graph into a graph of surface-runoff or inflow. This is a matter of great practical importance. First, it makes it possible to determine directly, although approximately, the coefficient K_s and the exponent M in the surface-runoff equation $q_s = K_s\delta^M$ for large areas in the manner given elsewhere by the author for small areas (Surface-runoff phenomena, Part I--Analysis of the hydrograph, Pub. 101, Horton Hydrologic Lab., 1935). Without some such method of correction for channel-storage the law of surface-runoff for large areas cannot be obtained directly from runoff-graphs.

The method above given of approximate correction for channel-storage during rising stages applies only in case of sharp-crested outflow-graphs or relatively short storms. The method can probably be extended with modification to long storms where the channel outflow-rate becomes nearly constant for a considerable time preceding the beginning of recession.

Relation of channel-storage to outflow-rate--Later on this subject will be treated analytically. Certain relationships may, however, be more clearly understood by means of a simple illustration. Referring to Figure 3, the lines aa' and bb' show, respectively, the volumes of channel-storage corresponding to the same discharge-rate for receding and rising stages, respectively. It will be noted that the volume of channel-storage at the same outflow-rate is materially greater for rising than for receding stages. It is sometimes assumed that the reverse is true, for the reason that during rising stages the slope is greater and consequently the velocity at a given gaging-section is greater at a given stage than for the same stage during receding stages. Hence if the channel-storage was the same in both cases, the volume of channel-storage for a given outflow-rate would be less for rising than for receding stages. Instead it is greater. The reason is that the volume of channel-storage is in general increased by a larger amount than the discharge-rate, as a result of the increase of slope during rising stages.

Figure 4 shows schematically profiles of a stream during rising and receding stages. For the rising stage, line a, the flood or stream-rise is still in the stream-channel upstream from the outlet O. For the receding stage the greater part of the flood-wave has passed downstream from O. At the point O the relation of stage to discharge may usually be expressed by $q_c = K_ch^M$, where M depends on the form of channel-section. From Manning's formula $K_c = 1.486\ \sqrt{S}/n$. Ordinarily the channel-length L is measured in miles, whereas the maximum departure Δ of the stream-stage from the normal profile does not exceed a few feet. The normal slope at the outlet O is $(H - h)/L$. The maximum and minimum slopes are, respectively:

$$\text{Maximum slope} = [H - h + (\Delta_1/2)]/L \quad \text{and} \quad \text{minimum slope} = [H - h - (\Delta_2/2)]/L$$

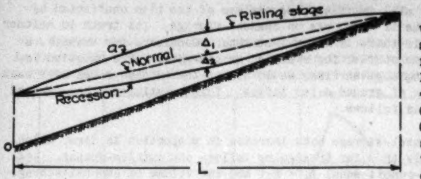

FIG. 4 -STREAM - PROFILE DURING RISING AND RECEDING STAGES

The discharge-rate at a given stage varies as $\sqrt{S}$. For example, for a medium-size stream or moderate slope and with a fall of about five feet per mile, if $L = 100{,}000$ feet and $H = 100$ feet, then if $h = 10$ and during a flood $\Delta_1 = 10$, $S = 0.001$. During recession, if $\Delta_2 = 8$, $S = 0.00084$. The normal slope for the same stage is 0.0009. During rising stages the slope is increased 11 per cent while during falling stages it is decreased 9.3 per cent. For much steeper streams h and Δ are so small relative to H that effect of variations of slope on the discharge during the passage of a flood is negligible. The effect of different percentages of variation in slope on the discharge-rate at the outlet are shown in the following table, where variation of slope is expressed as a percentage of the normal slope at the same stage, and variation of discharge is expressed as a percentage of that for normal slope at the same stage.

Effect of slope-variation alone

Departure from normal slope, per cent (1)	Departure from normal discharge, per cent	
	Rising stages (2)	Falling stages (3)
0	0	0
2	1.00	1.00
4	2.00	2.00
6	2.95	3.05
8	3.92	4.08
10	4.88	5.13
12	5.83	6.19
14	6.77	7.26
16	7.70	8.35
18	8.63	9.45
20	9.54	10.56

The variation of discharge for a given variation of slope is greater for falling than for rising stages. The departure of slope from the normal is usually greater for rising than for falling stages. It will be readily seen from Figure 4 that the variation of channel-storage with varying slope is relatively much greater than the variation of discharge. For example, for a rectangular channel, with $h = 10$, $L = 100{,}000$, and width w_0 at the outlet = 200 feet, the channel-storage for a normal stage will be $1/3w_0hL = 66{,}667{,}000$ cubic feet. The length of the flood-wave is usually so great relative to its height that the curvature of the superposed flood-wave may be neglected and its profile may be considered as triangular. In the case under consideration the superposed channel-storage above normal stage may be subdivided into three pyramids, the aggregate volume of which is 21,333,000 cubic feet or roundly an increase of one-third over that for the normal profile at the same stage. During recession the channel-storage is less than normal by a volume bearing about the same relation to that for rising stages that Δ_2 bears to Δ_1. It will be readily seen that variation of slope during passage of a stream-rise produces much larger variations in channel-storage than in discharge.

Effect of a constant source of inflow on channel-storage depletion--The author has shown in another paper (Pub. 101, Hyrton Hydrologic Lab., Surface-runoff phenomena, Part I, 1935) that given the pluviograph, the infiltration-capacity f, and the constants K_s and M in the overland-flow equation $q_s = K_s\delta^M$, the graph of surface-runoff can be determined. A channel outflow-graph, or runoff-graph in the ordinary sense, is the graph of surface-runoff as modified by channel-storage and ground-water inflow. The remainder of this paper is devoted to the application of the storage-equation to the determination of the channel-outflow graph where the surface-runoff or channel-inflow graph is given.

In the application of the unit-graph method of Sherman, or the pluviograph method of Bernard, and in the analysis of the hydrograph by the author's method and in many hydrologic problems, it is assumed that if a ground-water depletion-curve is drawn underneath a graph of a stream-rise, the remaining portion of the hydrograph will represent the regimen of the rise unaffected by ground-water. This would clearly be true if there was no channel-storage. Its truth is neither obvious nor is it in fact exactly true if there is channel-storage. Consider, for example, a constant rate of channel-inflow from some source, for example, ground-water. The question is, if the ground-water was eliminated during a given rise, would all of the outflow-rates have been decreased by an amount equal to the rate of ground-water inflow. This question may be answered for rising stages in a particular case as follows.

Assume that surface-runoff and channel-storage both increase in proportion to time, which, as has already been shown, will be nearly true for triangular inflow- and outflow-graphs. Let the rate of channel-inflow from surface-runoff equal $I_s = K_1 t$ and the volume of channel-storage equals $S_c = K_2 t$. If there is also a constant source of inflow at the rate q_g, then the storage-equation gives $(I_s + q_g)\, dt = q_c\, dt + dS_c$, or $K_1 t\, dt + q_g\, dt = q_c\, dt + K_2\, dt$, and

$$q_c = (K_1 t - K_2) + q_g \tag{17}$$

This shows that under the assumed conditions the constant source of inflow increases the channel outflow-rate during rising stages by an amount exactly equal to the rate of constant inflow; in other words, if on an observed channel outflow-graph, a base-line is drawn corresponding to the constant inflow-rate q_g, the ordinates of the graph above this base-line will represent the graph of channel-outflow exactly as it would have been had there been no constant source of inflow. This particular problem arose in connection with the effect of diversion from Lake Michigan into the Illinois River, and the following example is derived from a study made in that connection. The solution was obtained by the use of finite time-increments in conjunction with the storage-equation. For the sake of generality the water derived from a constant source of inflow is designated "blue water," as distinguished from surface-runoff, or "red water."

The principal results of the computation are shown graphically on Figure 5. Here line A is the graph of total inflow, including blue water; lines B and D are graphs of outflow and stage with blue water present; and lines C and E are graphs of outflow and stage as they would have been with no blue water present. The intercept between lines D and E shows the changes of stage, and intercepts between lines B and C show changes of outflow-rate resulting from the presence of blue water. These intercepts have been separately platted, as shown by lines F and G.

Line F shows the amount the outflow-stages were increased, and line G shows the amount the outflow-rate was increased by the presence of blue water.

It will be noted that a constant inflow of blue water during the passage of a stream-rise does not increase the stream-stage by a constant amount but by an amount which is a maximum at the beginning of the rise, decreasing to a minimum at the crest, and then gradually increasing.

As regards channel outflow-rates in this example, a constant rate of inflow of blue water has a slight but only a slight effect on the rate of outflow of red water until after the flood-crest has passed. It is to be noted that neither equation (17) nor this example applies to conditions of recession after surface-runoff has ended.

In connection with the analytical treatment of the subject it will be shown that the presence of a constant inflow of ground-water may greatly prolong the time required for the stream to recede to an outflow-rate equal to the ground-water inflow if the latter is constant. As a rule, the ground-water inflow-rate decreases during the recession of a stream-rise, and the time required for the outflow-rate to recede to a point where it equals the average ground-water inflow-rate is considerably less than if the ground-water inflow-rate was constant.

From the preceding it appears that a constant inflow of ground-water behaves, as regards outflow from the channel, much as if the red and blue water were separated and the blue water occupied a constant fraction of the width of the channel. Ground-water inflow is not usually constant, but during recession the ground-water flow and storage-depletion take place at more or less proportionate rates. This fact tends to emphasize the resemblance of the effect of ground-water to that of a constant reduction of width of channel for recession-conditions but tends to invalidate this relation during rising stages.

Channel-outflow graph--rising stages--with constant ground-water inflow--If inflow from surface-runoff occurs at a constant rate q_s, as is nearly the case in the latter part of a long storm, then, from the storage-equation, letting $b = (q_s + q_g)$, or the total constant or base-flow, $b\,dt = q_c dt + dS_c$. From equation (5), $S_c = K_{cs} q_c^{1/M}$ and $dS_c = (K_{cs}/M)\, q_c^{M'}\, dq_c$, where $(1-M)/M = M'$. Then

$$t = \int (K_{cs}/M)\, q_c^{M'}\, dq_c/(b - q_c) \tag{18}$$

This is the equation of the rising side of the outflow-graph with constant channel-inflow. If M' is fractional the integrand can be rationalized by substituting $z^r = q_c$, where r is the denominator of M'. The equation can then always be integrated by the method of partial fractions.

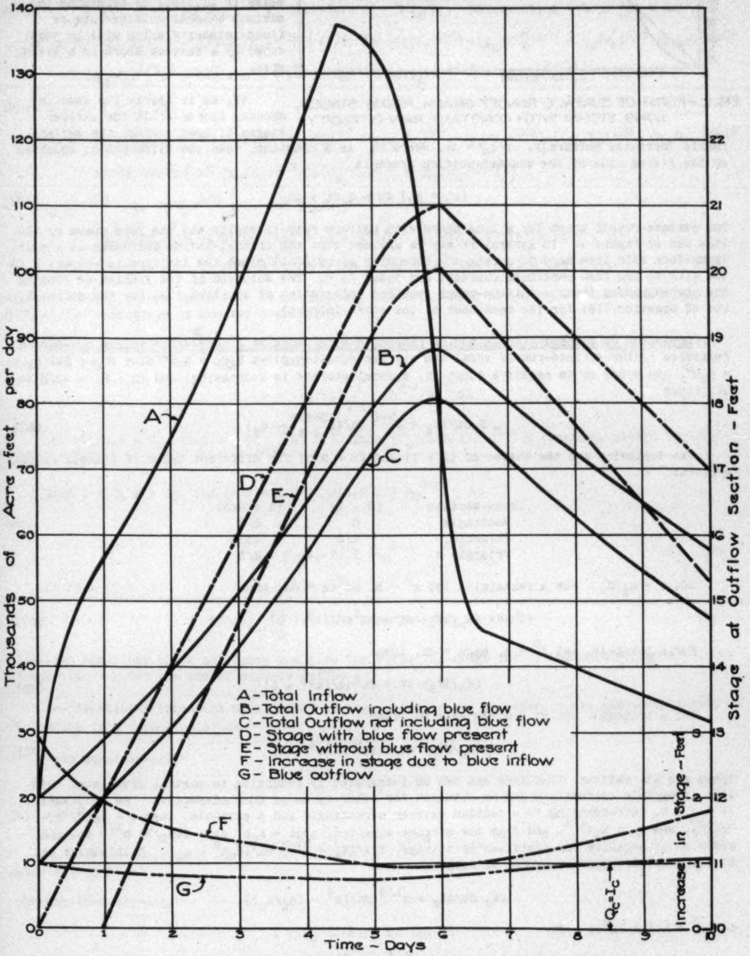

FIG. 5 - EFFECT OF CHANNEL-STORAGE AND OF A CONSTANT BLUE INFLOW ON THE REGIMEN OF A RIVER-FLOOD

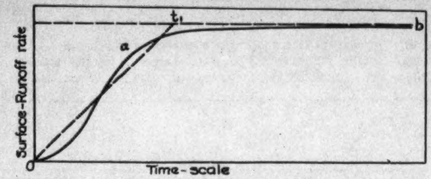

FIG. 6 - FORM OF SURFACE-RUNOFF GRAPH, RISING STAGES, LONG STORM WITH CONSTANT RAIN-INTENSITY

This equation is of great practical importance but the integrals cannot be given here. Since it is long storms that as a rule produce maximum runoff-intensities, equation (18) makes it possible to determine the maximum channel outflow-rate or flood-intensity which will be produced by a maximum storm on a given area.

If, as is nearly the case in shorter storms or in the earlier stages of long storms, the surface-runoff increases uniformly, or $q_s = at$, where a is a constant, then the differential equation of the rising side of the channel-outflow graph is

$$(at + q_g)\ dt = q_c dt + dS_c \tag{19}$$

The surface-runoff graph for a long storm with uniform rain-intensity has the form shown by the line oab of Figure 6. In general it may be assumed that the channel-inflow increases at a nearly uniform rate from zero to a rate σ = intensity of rainfall minus the infiltration-capacity in the time t_1 and then continues constant and equal to σ. The solution of the problem of finding the corresponding channel outflow-graph requires integration of equation (19) for the period t_1 and of equation (18) for the remainder of the storm-interval.

Depletion of channel-storage during recession with constant ground-water inflow q_g--During recession (after surface-runoff ends) the storage-equation gives $q_g dt = K_c h^R\ dt + dS_c$. But $S_c = K_z h^S$, and since dh is negative (that is, channel-storage is decreasing) and $(S - R) = -2/3$ in all cases

$$K_c dt/SK_z = h^{S-1}\ dh/(h^{S+2/3} - q_g) \tag{20}$$

The following are the values of $(S - 1)$ and $(S + 2/3)$ for different types of channel cross-section:

Cross-section	(S - 1)	(S + 2/3)
Rectangle	0	5/3
Parabola	1/2	13/6
Triangle	1	8/3

Let $b = q_g/K_c$. For a rectangle, let $z^3 = h$, $3z^2 dz = dh$, then

$$(K_c/SK_z)\ dt = 3z^2 dz/(z^5 - b) \tag{21}$$

For a parabola, let $z^6 = h$, $6z dz = dh$, then

$$(K_c/SK_z)\ dt = 6z^8 dz/(z^{13} - b) \tag{22}$$

For a triangle, let $z^3 = h$, $3z^2 dz = dh$, then

$$(K_c/SK_z)\ dt = 3z^5 dz/(z^8 - b) \tag{23}$$

These are all rational fractions and can be integrated by reduction to partial fractions. Similar integrable expressions can be obtained for other forms of channel-section. As an example: If $R = 2.0$, corresponding to a section between a rectangle and a parabola, then $q = K_c h^2$, $h = \sqrt{q/K_c}$, and $S_c = K_z h^{4/3}$, and from the storage-equation, $q_g dt = K_c h^2\ dt + (4K_z/3)\ h^{1/3}\ dh$, and, since dh is negative for depletion of storage, $3dt/4K_z = h^{1/3}\ dh/(K_c h^2 - q_g)$. Multiplying and dividing the denominator by K_c, we have

$$3K_c\ dt/4K_z = h^{1/3}\ dh/[h^2 - (q_g/K_c)] \tag{24}$$

Let $z^3 = h$ and $3z^2 dz = dh$,

$$K_c t/4K_z = \int z^3 dz/[z^6 - (q_g/K_c)] \tag{25}$$

From Hirsch's "Integral tables" (London, 1823, p.61)

$$\int z^3 dz/[z^6 - (q_g/K_c)] = - (1/6bk^2) \left\{(1/2) \ln [(z^4 + k^2 z^2 + k^4)/(z^2 - k^2)^2] - \sqrt{3} \tan^{-1} [\sqrt{3}\, z^2/(2k^2 + z^2)]\right\} + \text{constant}$$

where $k = \sqrt[6]{-a/b}$, $a = - q_g/K_c$, $b = 1$, therefore $k = \sqrt[6]{q_g/K_c}$. Substituting values for k and z

$$\int z^3 dz/[z^6 - q_g/K_c)] = -[1/6(q_g/K_c)^{1/3}] \left\{ (1/2) \ln [(q/K_c)^{2/3} + (q_g q/K_c^2)^{1/3} + (q_g/K_c)^{2/3}]/[(q/K_c)^{1/3} - (q_g/K_c)^{1/3}]^2 - \sqrt{3} \tan^{-1} \left(\sqrt{3}\, (q/K_c)^{1/3}/[2(q_g/K_c)^{1/3} + (q/K_c)^{1/3}]\right)\right\} + \text{constant}$$

Where $t = 0$, $q = q_o$ and

$$\text{constant} = [1/6(q_g/K_c)^{1/3}] \left\{(1/2) \ln [(q_o/K_c)^{2/3} + (q_g q_o/K_c)^{1/3} + (q_g/K_c)^{2/3}]/[(q_o/K_c)^{1/3} - (q_g/K_c)^{1/3}]^2 + \sqrt{3} \tan^{-1} \left(\sqrt{3}\, (q_o/K_c)^{1/3}/[2(q_g/K_c)^{1/3} + (q_o/K_c)^{1/3}]\right)\right\}$$

Let $(q_g/K_c)^{1/3} = a$, $(q/K_c)^{1/3} = b$, and $(q_o/K_c)^{1/3} = c$, then

$$(3K_c a/2K_z)t = (1/2) \ln [(c^2 + ac + a^2)(b - a)^2/(c - a)^2(b^2 + ab + a^2)] \quad \sqrt{3} \tan^{-1}[\sqrt{3}\, c/(2a + c)] + \sqrt{3} \tan^{-1}[\sqrt{3}\, b/(2a + b)] \tag{26}$$

If the constant ground-water flow is eliminated, the derivation of the equation of the recession-side of the hydrograph is greatly simplified.

Channel-storage equation, excluding ground-water--The storage-equation gives, since dh is negative, $dS_c = SK_z h^{S-1} dh = K_c h^R\, dt$ and

$$t = (K_z/K_c) \int_{h_0}^{h} (h^{S-1}/h^R)\, dh \tag{27}$$

Let $(K_z/K_c) = C_c$, then $t = C_c \int_{h_0}^{h} h^{S-R-1} \cdot dh = [C_c/(S-R-1)]\, h^{S-R}$ + constant, except in case $(S-R) = -1$.

When $t = 0$, $h = h_0$, and constant $= [C_c/(S-R-1)]\, h_0^{S-R}$

and

$$t = C_c/(S-R-1)\, (h_0^{S-R} - h^{S-R}) \tag{28}$$

If $(S-R-1) = -1$,

$$t = C_c \int_{h_0}^{h} (dh/h) + \text{constant} = C_c \ln (h_0/h) \tag{29}$$

These two equations cover all cases and give the recession-stage due to channel-storage depletion at any time t after the end of surface-inflow.

The quantities known are usually not h_0 and h_g but q_0 and q_g, where q_0 is the initial rate of outflow from channel-storage.

From equation (1),

$$h = (q_c/K_c)^{1/R} \tag{30}$$

This gives

$$t = [C_c/(S-R-1)]\, [(q_0/K_c)^z - (q/K_c)^2] \tag{31}$$

where $z = (S-R)/R$.

For $(S-R-1) = -1$,

$$t = C_c\, (S-R)/R \ln (q_0/q) \tag{32}$$

As already shown, $(S-R) = -2/3$ under normal conditions. The exponent z is therefore negative and both equations (31) and (32) indicate that the time required for exhaustion of channel-

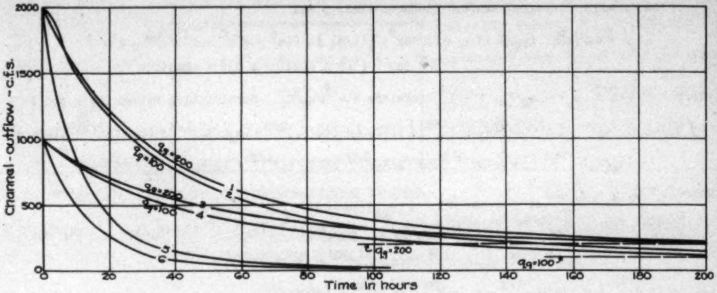

FIG. 7 - CHANNEL-OUTFLOW GRAPHS DURING RECESSION, WITH AND WITHOUT GROUND-WATER FLOW (FROM EQUATIONS 21 AND 31)

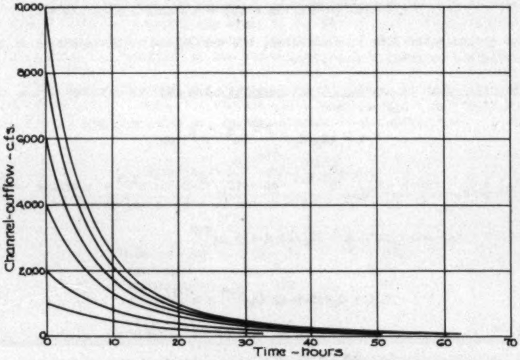

FIG. 8.- CHANNEL-OUTFLOW GRAPHS DURING RECESSION, NO GROUND-WATER FLOW (FROM EQUATION 31)

storage is infinite if there is no ground-water flow present.

Figure 7 shows channel outflow-graphs during recession computed by equations (21) and (31) for q_c = $50h^2$ and S = 30,000,000 $h^{4/3}$ cubic feet. The conditions correspond approximately to those of a typical drainage-basin in eastern United States with moderately high stream-density and an area of about 300 square miles. The curves on Figure 7 represent the following conditions:

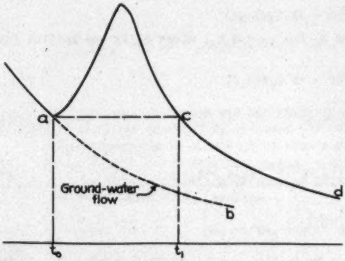

FIG. 9 - DETERMINATION OF BASE OF SURFACE-RUNOFF GRAPH

Curve	Equation	q_0, cfs	q_g, cfs
1	21	2000	200
2	21	2000	100
3	21	1000	200
4	21	1000	100
5	31	2000	0
6	31	1000	0

Figure 8 shows channel-storage depletion-curves for the same conditions but with zero ground-water inflow (equation 31) with initial rates of channel-outflow ranging from 10,000 to 1000 cfs.

From Figure 7 it will be seen that a constant ground-water inflow greatly prolongs the time required for exhaustion of channel-outflow at the end of a stream-rise and extends the base of the hydrograph about in proportion to the ratio of the rate of inflow of ground-water to the total initial outflow-rate q_0.

Figure 8 shows that if no ground-water inflow is present, the recession-lines during exhaustion of channel-storage come so close together after a certain time that for practical purposes no great error results from the assumption that the duration of recession is constant and independent of the initial rate of outflow from channel-storage. Both the analytical treatment of the subject and the examples given show that the time required for complete exhaustion of channel-storage after surface-runoff ends is infinite in case either (1) there is constant ground-water inflow or (2) zero ground-water inflow.

Usually there is more or less ground-water inflow during a stream-rise but the rate is not constant. During recession, after surface-runoff ends, the rate of ground-water inflow almost invariably decreases. Under these conditions the time required for the return of channel-outflow either equal to the initial or equal to the average ground-water inflow-rate will be finite. After the return of the outflow-rate to equality with the initial ground-water inflow-rate there will still be some channel-storage remaining, derived from surface-runoff. The source of the channel-storage, whether from surface-runoff or ground-water, has no effect whatever on the outflow-rate, other things equal. Consequently the regimen of recession after the outflow-rate returns to equality with the initial ground-water inflow-rate will be precisely the same as if there had been no rise due to surface-runoff. This is shown by Figure 9. At the time t_1 the channel outflow-rate has returned to equality with the ground-water inflow-rate at the initial time t_0. The line ab is the channel outflow-rate from ground-water as it would have been had no rise occurred. Since both the channel-storage at the point c and the channel outflow-rate are the same as at a, the arc cd is a duplicate of the arc ab moved forward by the time-interval t_1. The time-base of tne surface-runoff graph, exclusive of ground-water, may therefore, for practical purposes, be taken as equal to ac or t_1. This result is subject to the qualification that it holds strictly true only in case the stream-profile and consequently the volume of channel-storage are normal at the time t_1. If, as is apparently the rule, the volume of channel-storage at the time t_1 is less than for the corresponding stream-stage at the outlet at the time t_0, then the subsequent arc of the channel outflow-graph will be approximately but not exactly represented by an arc of the ground-water depletion-curve.

Application of the unit-graph method--Some of the preceding results have an important bearing on the hydrologic basis of the unit-graph and other similar methods of estimating surface-runoff.

(1) It will be noted that the correct time-base for a unit-graph, excluding ground-water, is the time elapsed from the beginning of the rise until the channel-outflow again returns to equality with the ground-water outflow-rate at the beginning of the rise.

(2) This time-base is not constant for rises of different intensities, other things equal, in cases where there is ground-water inflow to the channel.

(3) It has been shown that there are large variations in the volume of channel-storage corresponding to the same channel discharge-rate in different storms on the same area. This is true of the storms used in determining the distribution graphs for different streams as given in Water-Supply Paper 772. This variation in unit channel-storage sometimes amounts to 100 per cent or more. The greater the volume of channel-storage, other things equal, the greater the degree of modulation by surface-runoff, and the longer the duration of channel-outflow. This variation of channel-storage apparently accounts for much if not all of the variation in the distribution-graphs for the same drainage-basins in different storms shown in Water-Supply Paper 772. These variations are considerable. For example, in the case of the Muskingum River at Dresden, Ohio, Water-Supply Paper 772 shows a crest-runoff ranging from 19 per cent to 39 per cent of the total runoff in different distribution-graphs. This would produce a variation of more than 100 per

cent in the computed runoff crest-intensity. Variations of nearly the same order occur in case of other streams and similar variations occur in the distribution-graphs as regards the duration of runoff. Since these graphs were determined from carefully selected, isolated storms, with little initial channel-storage, they evidently represent the best possible results obtainable by this method if variation of channel-storage is not taken into account.

The law of storage

$$\text{Inflow} = \text{Outflow} + \text{Gain or} - \text{Loss of storage}$$

shows that the ratio of runoff-intensity for a given time-interval to total surface-runoff cannot remain constant with varying runoff-intensities unless the volume of channel-storage varies by the same percentage. The validity of an equation is not affected if all its terms are multiplied by the same quantity. Applying the subscripts 1 and 2 to two different storms, with different runoff-intensities I_1 and I_2, the storage-equation gives in the two cases $I_1 = (O_1 + S_1)$ and $I_2 = (O_2 + S_2)$. If the ratio $(O_2/O_1) = C$, then the second equation may be written $O_2 = C\,O_1 = (CI_1 - CS_1)$. In these equations I, O, and S relate, respectively, to surface-runoff, channel-outflow, and channel-storage, for a chosen time-interval. This shows that the channel outflow-intensity for a given time-interval will be increased in the ratio C if and only if the channel-storage is increased in the same proportion.

It seems quite certain that greater accuracy may be attained in the application of the distribution-graph to a succession of runoff-days if, instead of using the same graph throughout, the distribution-graph applied to each day is modified in a manner dependent on the amount of residual channel-storage remaining from preceding runoff.

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BED-LOAD TRANSPORTATION AND THE STABLE-CHANNEL PROBLEM

Samuel Shulits and W. E. Corfitzen

Introduction

Recent studies [see 1 of references at end of paper] seem to indicate that there is no definite basis for selection of a design formula for a non-silting and non-scouring channel. One reason for this lack is the failure or inability, except in the case of the Lacey formula, to include the effect of the size or mechanical composition of the bed-material and the solids load, as well as the magnitude of the load.

In connection with certain studies dealing with the Imperial Desilting Works of the All-American Canal, it was necessary to determine the maximum size of material that might be delivered to the desilting works by the Colorado River and also what sizes could be carried in the channels beyond the canal-intake. Various formulas or experience data were considered, but only those judged after careful analysis to be relevant, usable, and most reliable were employed. Since, as will be shown immediately below, these formulas yield a definite particle-size criterion for a stable channel in erodible material, in that they correlate the maximum transportable size and certain hydraulic channel characteristics, they are presented here together with a comparison of the results obtainable with them.

The largest particles are carried along the bottom of the channel by the tractive force of the stream, that is, as part of the bed-load. This obviates consideration of the suspension-form of transportation, about which little of practical application is yet known. Since the particle-size determined is the largest that can be moved along the bottom, it can be inferred that no silting or aggradation should occur where material of this size or smaller is being transported. It also follows that a channel of material of this critical size or larger cannot be scoured or degraded. Hence, the maximum particle-size that can be transported as part of the bed-load represents the size of material which would create a non-silting, non-scouring channel. This is shown diagrammatically on Figure 1. Actually, however, there is disagreement between the results given by the individual formulas, so that the two areas shown on Figure 1 are separated by a band and not a single line as in the ideal case.

Bases of computation

For determination of the size of the bed-load material, there can be said to exist five general types of formulas or experience data, as follows:

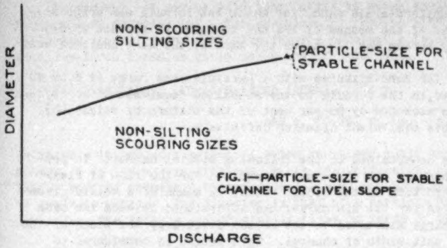

FIG. I—PARTICLE-SIZE FOR STABLE CHANNEL FOR GIVEN SLOPE

(I) Bed-load formulas--These are derived from tests in experimental drag-flumes and correlate the bed-load, the energy-gradient, the discharge, and the size of material.

(II) Tractive-force formulas--Also obtained from drag-flume tests and correlating tractive force and size of grain.

(III) Observed natural tractive forces--As a result of observations on natural streams, there are tables of the tractive forces required to move given sizes of material.

(IV) Competent mean velocities--Mainly experience tables giving the mean velocity that will move a given size. In some cases, a formula correlating these two factors.

(V) Competent bottom-velocities--Same as (IV), except that the bottom-velocity is used. This group will not be considered, because of the great uncertainty that would exist in the estimate of the bottom-velocity.

(I) Bed-load formulas

Three such formulas will be considered below. To all of them, except the Schoklitsch formula, the objection may be raised that, being based on experimental flume-tests, they do not hold for a natural stream.

(a) Schoklitsch bed-load formula [2]--This has been verified for three European streams. It is based mainly on Gilbert's experiments [3], so that its use is tantamount to employing Gilbert's data. The formula is

$$G = (86.7/\sqrt{D})\, S^{1.5}\, (Q - Bq_0) \qquad (1)$$

in which G is the bed-load in pounds per second, D is the grain-diameter in inches, S is the energy-gradient, Q is the instantaneous discharge in cusecs, B is the width of river in feet, and q_0 is the critical discharge, that is, that at which movement begins, in cusecs per foot. The value of the latter is

$$q_0 = 0.00532D/(S^{4/3}) \qquad (2)$$

Now, the size of material moved will be a maximum when the bed-load is zero. This condition applied to equation (1) yields

$$D_{max} = 4770(QS^{4/3}/B) \qquad (3)$$

in which D_{max} is in mm. This is either the diameter of a uniform-grain material (diameter of a sphere having volume of average particle) or the so-called "equivalent diameter" in the case of a natural mixture [2]. Calculation of a number of examples has shown that the equivalent-grain diameter is roughly that exceeded by 40 to 60 per cent of the mixture by weight.

As can be seen on Table 3 under the Schoklitsch bed-load formula, Gilbert measured the slope of the bed, a point which has been criticized. However, the bed-slope is closer in value to the energy-gradient than is the water-surface slope, so that the Schoklitsch bed-load formula is still a reliable instrument for the hydraulic engineer.

(b) Swiss Federal Institute of Technology (SFIT) bed-load formula [4]--For material of a specific gravity of 2.6 and the form of natural river-debris, the formula is

$$q^{2/3}\, S/D = 17 + 0.4\, (g^{2/3}/D) \qquad (4)$$

in which q is the discharge in kg per sec per meter of width, D is the diameter of grain in meters, g is the bed-load in kg per sec per meter of width, and S is the energy-gradient.

The grain diameter of a so-called uniform-grain sand, for which the formula was originally derived, is defined as the geometric mean of the meshes of the two consecutive screens used to separate the test sand. The mesh of any screen was $\sqrt{2}$ times the mesh of the next smallest one.

Formula (4) was found to hold also for sand-mixtures with a particle-size range of 6 to 40 mm. In this case the diameter to be used in the formula is the so-called "equivalent" or "effective" diameter, namely, the size that is exceeded by 65 per cent of the mixture by weight [5]. More tests are necessary to determine this equivalent diameter definitely.

The discharge per foot of width was ascertained in the following special manner: In preliminary tests the coefficient of roughness of the flume was determined for the flow of clear water and a smooth bottom of the same condition as the sides. Then, by means of a method given by A. Einstein [6], the flow cross-section (or the discharge) was apportioned between the side walls and the bottom. The partial discharge allocated to the bottom divided by the width of the flume was taken to be the discharge per unit width of channel. This method is considered to eliminate the effect of side-wall roughness.

This bed-load formula was deduced from the results obtained with two uniform-grain sands in the flume of the SFIT and Gilbert's measurements for three of his uniform sands. The constants, a = 17, and b = 0.4, are for a specific gravity of 2.6 and material having the form of natural river-debris.

Experiments with a river-model (scale 1:100) revealed that formula (4) is valid also for brown-coal cinders, only the constants changing because of the different specific gravity [5].

Imposition of the condition that the bed-load must be zero and conversion into English units yields

$$D_{max} = 1200\ (Q^{2/3}\ S/B^{2/3}) \tag{5}$$

where D_{max} is in mm, Q is in ft^3 sec^{-1}, and B is in feet.

(c) United States Waterways Experiment Station formula [7]--

$$G = (1/n)\ [(ds - d_oS_o)^{k_2}/k_1] \tag{6}$$

in which G is the bed-load in pounds per foot per hour, n is the roughness-coefficient in the Manning formula, d is the depth in feet, S is the water-surface slope, d_oS_o is the value of the depth-slope product for the given sand-mixture at the time of commencement of movement, while k_1 and k_2 are constants whose values are dependent upon the physical characteristics of the bed-load material.

Both k_1 and k_2 are functions of the size and gradation of the material transported, but the United States Waterways Experiment Station apparently made no effort to secure a numerical relation. The writers could find none by inspection. Furthermore, the condition of zero bed-load results in $dS = d_oS_o$ with no given means of evaluating d_oS_o. Hence, although some relationship might be deduced from the experimental results, this equation will not be given further consideration here.

(II) Tractive-force formulas

In the tractive-force formulas, the physical characteristics of the moving material are expressed in terms of the tractive force of the stream, namely, wRS, in which w is the unit weight of water, R is the hydraulic radius, and S is the energy-gradient. They are mainly empirical. Four such formulas, those of Schoklitsch, Krey, Kramer, and the United States Waterways Experiment Station are considered below.

The significance and applicability of tractive forces determined in an experimental flume of the usual dimensions are moot. Kramer [8] defined the critical tractive force as that which effects a general movement of the material up to and including the largest component particles. He concluded from his experiments and other independent confirmations that the critical tractive force is constant for a given sand-mixture, that is, it is not determined by R alone, or by S alone, but is solely a constant product wRS. The SFIT investigations [5, p. 96] indicated no connection between tractive force and bed-load--for a constant value of the former, the load was different for different depths of flow. Although these two findings are not incompatible, they show the need for further clarification of the concept of "tractive force."

In general, it may be said that little is known about the critical tractive force of very fine-grained material [9]. The experimental results with coarser grains can be expressed in the following general form: Tractive force = constant x (diameter)^n, where n is an exponent. The tractive-force formulas given below are of this form.

(a) Schoklitsch tractive-force formula [10]--

$$wRS = \sqrt{0.201\ w_1\ (w_1 - w)\ \lambda\ D^3} \qquad (7)$$

in which w is the unit-weight of water in kg per cubic meter, R is the hydraulic radius in meters, S is the energy-gradient, w_1 is the unit-weight of the transported material, λ is a form-factor varying between 1.15 and 1.35 for sand and here assumed to be 1.25, and d is the diameter of grain in meters. The diameter is that of a particle having the same volume as the test-particle. The formula was originally given in terms of the volume.

This formula is for a single grain resting freely on a bed of uniform grains of the same size and gives the critical tractive force at which the particle just begins to move. In a natural stream the bed-load material (geschiebe) is not uniform, of course, but in most cases it is derived from the bed-material and, hence, is of the same size-range, though not uniform. For this reason, it is considered to be applicable to the stream-problem investigated here. This will be discussed again below in some greater detail.

It has been said [10c, p. 39] that the condition for which formula (7) was set up does not occur in nature. Inspection of Austrian mountain streams by Mr. Shulits during the dry season showed them to be covered with large stones and cobbles, all apparently of the same size, leaning downstream. They formed a protective or erosion pavement that had to be moved before the underlying bed could be scoured.

Transposition of formula (7) and conversion yields

$$D = 439\ (RS)^{2/3} \qquad (8)$$

where D is in mm and R is in feet.

There is another critical tractive-force formula by Schoklitsch [10b] which will be given for general purposes, although it is not used here. It is for the critical tractive force of a single stone of volume V resting on a bed of similar stones of volume $V_b < V$. This tractive force [9] is less than given by formula (7).

$$wRS = \sqrt{0.385\ w_1\ (w_1 - w)\ \lambda\ V} \Big/ \left(1 + \sqrt[4]{10.5[(V/V_b) - 1]}\right) \qquad (9)$$

The formula is for metric units, the volumes being in cubic meters, and the other symbols as defined by formula (7).

(b) Krey tractive-force formula [11, 9 (p. 1072), 10c (p. 38)]--

$$wRS = (0.045 \text{ to } 0.07)\ (w_1 - w)\ D \qquad (10)$$

which is dimensionally correct. The symbols have the same meaning as in the Schoklitsch tractive-force formula (7). The diameter is the median diameter, that is, 50 per cent of the mixture is both larger and smaller than this size.

The numbers 0.045 to 0.07 represent a variable coefficient, for the determination of which no rule is given. It will be assumed equal to 0.06, the mean of the limiting values. Formula (10) finally becomes

$$D = 3080\ RS \qquad (11)$$

in which D is in mm and R is in feet.

The formula is based on tests with sands that were practically uniform in size. The use of the "median" diameter is, therefore, somewhat misleading, since mixtures were not employed.

The critical tractive force given by formula (10) is that at which noticeable or lively movement occurs and, therefore, for a given size it will be higher than that obtained with the Schoklitsch tractive-force formula. This means that for a given tractive force the Krey formula should yield generally a smaller diameter than the Schoklitsch formula.

The reason for the criterion, "noticeable or lively movement," was that the purpose of Krey's tests was to determine the conditions necessary to insure such a movement in river-models with movable beds.

(c) Kramer tractive-force formula [7, 8, 10c]--

$$wRS = (100/6)\,(D/M)\,(w_1 - w) \qquad (12)$$

which is a dimensionally correct formula. D is the mean diameter obtained mathematically from the mechanical-analysis curve and M is the "uniformity-modulus." The latter is computed in the following manner: A mechanical-analysis curve is plotted with the percentages passing as ordinates and the grain-diameters as abscissas. The area bounded by the curve, the ordinate axis, and the horizontal line through 100 per cent is divided into two parts by a horizontal line through 50 per cent. The area below this 50 per cent line divided by that above it is the uniformity-modulus.

This formula is based on tests with three sands by Kramer himself, and the results obtained with other sands by Schaffernak (1 sand), Schoklitsch (5), Krey (3), Prussian Experimental Institute for Hydraulic Engineering and Naval Architecture (7), Engels (1), and Gilbert (4).

For a uniform-grain sand, M has the value, unity; for mixtures it is always less than unity; the greater the range between maximum and minimum grain-sizes, the closer does the modulus approach zero. As will be explained below and was intimated above under the Schoklitsch tractive-force formula, a uniform-grain sand will be used as a basis of comparison. Hence, M = 1 and formula (12) becomes finally

$$D = 11170\ RS \qquad (13)$$

where D is in mm and R is in feet.

Kramer defines his critical tractive force as that which effects a general movement of the material up to and including its largest component particles. This definition indicates that, in the last analysis, the purpose of his tests was the same as Krey's.

Although the range of critical tractive force of the data Kramer investigated was 0.00492 to 0.1115 lb ft^{-2}, the chart on which the data were plotted and which gives the line represented by his formula shows that the maximum tractive force actually employed was 113 g m^{-2} (0.0232 lb ft^{-2}). Only four points have a higher value.

(d) United States Waterways Experiment Station tractive-force formula [7]--

$$wRS = 0.0038\ \sqrt{D(w_1 - w)/M} \qquad (14)$$

in which R is in feet, w and w_1 are in lb ft^{-3}, and D is in inches. The diameter and M, the uniformity-modulus, are as defined for the Kramer formula.

In its final form for use in this study, this equation becomes

$$D = 66{,}600{,}000\ (RS)^2 \qquad (15)$$

in which D is in mm and R is in feet.

The basis of the United States Waterways Experiment Station formula is the data Kramer used plus the results of tests with eight mixtures conducted in the Experiment Station. The remarks made above under the Kramer formula relative to the range of the critical tractive force apply here also.

(III) Observed natural tractive forces

Certain agencies have observed in nature the critical tractive forces necessary to move given sizes of particles. The information available is of two types: (1) The critical tractive force necessary to move particles of stated sizes or between certain size-limits, to which class belong the data of the Nuernberg Agricultural Bureau (Kulturamt Nuernberg); (2) the critical tractive force required to move a size described in general terms, such as sand, coarse gravel, etc. In the latter group are the data given by Franzius and Kreuter.

(a) Nuernberg Kulturamt critical tractive forces--Table 1 gives the critical tractive forces at which the stated sizes just begin to move. These are the results of measurements by the Nuernberg Kulturamt [12] with material in its natural condition in the river.

Table 1--Critical tractive forces observed by Nuernberg Kulturamt

Description of material	Size	Critical tractive force
	mm	kg m^{-2}
Ordinary quartz-sand	0.20-0.40	0.18-0.20
Ordinary quartz-sand	0.4 -1.0	0.25-0.30
Ordinary quartz-sand	Up to 2.0	0.40
Round quartz-gravel	5-15	1.25
Loamy soil	.....	1.0 -1.2
Coarse quartz-pebbles	40-50	4.8
Flat limestone	10-20 thick 40-60 long	5.6

A plot of tractive force against particle-size was constructed from the tabulated data. There were two lines representing the size-limits as given. Since the tractive force for various river-discharges could be computed, the diameter of grain transportable by different flows could be read from the chart and plotted. As the maximum transportable size was desired, the branch of the chart corresponding to the upper limit was read.

(b) Franzius and Kreuter critical tractive force--According to Franzius [13], for stable channels, the allowable tractive force for ordinary sand is 1 kg m^{-2} (0.2 lb ft^{-2}) and for very coarse sand and gravel up to 1.5 kg m^{-2} (0.3 lb ft^{-2}).

Kreuter [14] states that 0.6 to 0.7 kg m^{-2} (0.12 to 0.14 lb ft^{-2}) will move coarse sand, while fine gravel in motion will come to rest at a tractive force of 1.25 kg m^{-2} (0.25 lb ft^{-2}).

Such general descriptions of size are much too indefinite, since what the size of "coarse sand, fine gravel, etc." may be will vary with the engineer, his experience, and the locality. For this reason no use was made of such data.

(IV) Competent mean velocities

A competent mean velocity is a velocity which is just able to move material [3, p. 35]. Usually in this group the particle-size is in general terms, while a definite figure is stated for the mean velocity required to barely move the size. The information is mostly in the form of tables or charts based on experience; sometimes empirical formulas correlating size and velocity. The latter are not considered in this discussion.

(a) Thrupp's competent velocities [15]--In an interesting paper, E. C. Thrupp presents a diagram showing a relation between hydraulic radius, mean velocity, and size of material moved or carried. It is based mainly on an interpretation of visual field-observations and the sizes are also described in general terms; the most definite being "size of peas" and "size of hen's eggs." Thus, its reliability is rather dubious and its applicability vague. Nevertheless, on the assumption that pea-size was about five mm, the discharge that would move this size was determined.

(b) Franzius competent velocities [16]--The mean velocities of Table 2 are given as causing "appreciable" movement.

Table 2

Material	Competent mean velocity
	m sec^{-1}
Fine sand and silt	0.5
Mortar sand	1
Packed, clayey or very coarse sand	1.5
Coarse gravel or firm clay (Klai)	2.0

These size-descriptions are too general to be considered further here.

Table 3--Experimen

Type of data	1--Bed-load formulas		II--Tractive-force formulas	
Designation	Schoklitsch (Gilbert)	Swiss Federal Institute of Technology	Schoklitsch	Krey
Criterion of movement	......	......	Commencement of motion of a single particle resting freely on a bed of material of like size	Beginning of no-ticeable or lively movemen
Type of traction	Stream	Stream	Stream	Stream
Number of sands tested	35	2 uniform-grain sands	2 porcelain spheres 5 quartz-sands 1 ore-bearing sand 2 slates	3 natural quartz sands
Uniform-grain or mixture	9 uniform-grain 26 mixtures	2 brown-coal cinder mixtures Unknown number of sand-mixtures	Single pebble on a bed of uniform-grain material of same size	Approximately uniform-grain
Specific gravity	2.69	Sand: 2.6 Brown-coal cinders: 1.25	Porcelain: 2.17 Quartz: 2.60 Ore-bearing sand: 3.70 Slate: 2.70	2.57 to 2.68
Range of particle-diameter, mm	0.305 to 7.01	Uniform sands: 5.05 and 28.6 Brown-coal cinders: 0.5 to 11.6 Sand mixtures: 6 to 40	Porcelain: 16.5 and 4.21 Quartz: 0.92, 1.24, 2.26, 4.05, and 6.52 Ore-bearing sand: 14 Slate: 12.3 and 30.7	0.30 to 0.45 0.45 to 0.60 0.60 to 1.00
Definition of diameter	Mean diameter: Dia. of sphere having volume of average particle; also equivalent dia. (see text)	Geometric mean diameter and equivalent diameter (see text)	Dia. of sphere having volume of test-pebbles	Median diameter (see text)
Tractive force, pounds per square foot	......	......	0.00574 to 0.1115	0.00463 to 0.0343
Total discharge, cubic feet per second	Gilbert: 0.093 to 1.119	Uniform sands: 0.762 to 162.5 Brown-coal cinders: 0.035 to 0.883	......	......
Discharge per foot of width, square feet per second	Gilbert: 0.138 to 1.695 Schoklitsch-Gilbert: 0.0672 to 2.69	Uniform sands: 0.656 to 24.74 (See text for special definition)	......	......
Mean velocity, feet per second	Gilbert: 0.68 to 5.19	......	......	......
Depth, feet	Gilbert: 0.037 to 0.735 approx.	Uniform sands: Up to 3.93	Up to 0.26	Up to 0.33
Hydraulic radius, feet	......	......	......	......
Width, feet	Gilbert: 0.23 to 1.96	Uniform sands: 1.16 and 6.56	......	0.61
Slope	Gilbert: 0.012 to 0.0404 bed-slope Schoklitsch-Gilbert: 0.012 to 0.055, bed-slope almost entirely	Brown-coal cinders: Energy-gradient, 0.00099 to 0.00104	......	......
Roughness	......	......	......	......
Is formula dimensionally correct?	No	No	No	Yes

ases of traction formulas

II--Tractive-force formulas		III--Observed natural tractive forces	IV--Competent mean velocities	Imperial Dam Site characteristics	Desilting works channels
Kramer	U. S. Waterways Exp.-Station	Nuernberg Kulturamt	Thrupp		
eneral movement of material up to and including its largest component particles		Particle just begins to move	......	Maximum transportable size desired	
Stream	Stream	Stream	Stream	Stream	Flume-traction in concrete channels; stream in rip-rap portion
24	32	......	......	......	......
5 uniform-grain 19 mixtures	5 uniform-grain 24 mixtures	......	......	Mixture	Mixture
2.57 to 2.70		......	......	2.65	2.65
0 to 6.3	0 to 9.42	0.2 to 50	......	0.045 to 0.6	
Mean diameter (see text)	Mean diameter (see text)	......	......	......	......
.00492 to 0.0232	0.0048 to 0.0232	0.037 to 1.15	......	0.04 to 0.30	0.114 to 0.251
......	......	......	......	Max. 150,000	2000 to 4000
......	......	......	......	Max. 1,280	46 to 89
......	......	......	1.75 to 40	8 at 60,000 c.f.s.	5.98 to 7.41
......	......	......	......	7 at 60,000 c.f.s.	7.4 to 12.0
......	......	......	0.05 to 60	Assumed same as depth	5.8 to 8.4
......	......	......	......	1200	22.5 to 87.1
......	......		....	Water-surface: 0.000189 to 0.000379	Energy-gradient: 0.000288 to 0.000478
......	......	......	......	......	0.014 to 0.0225
Yes	No	......	......	......	......

Discussion of formulas

To assist in the determination of the range of applicability of the foregoing information, Table 3 is presented. It is a compilation of the data on which the formulas were based, including a description of the test-conditions and extent.

Where there are blanks in the Table, either the data were not given in the source or the literature was not available. The Kramer and United States Waterways Experiment Station formulas are based on the results of various experimenters. The publications dealing with these two formulas do not give all the data desired for the Table and the original sources could not be obtained.

The differences in the "criterion of movement" for the critical tractive force should be carefully noted.

It would have been desirable and valuable to include in the Table the Reynolds' and Froude's numbers for the test-channels and the particles. Only Kramer [8] and the United States Waterways Experiment Station [7] give the channel Reynolds' number based on the mean velocity and the hydraulic radius, but this is not tabulated here.

Some relevant publications by Casey [17], Gavrilenko [18], and Goncharov [19] became available too late for study.

All the formulas or data in Table 3 are for stream-traction [3, pp. 15 and 199] which occurs when the bed of a natural stream carrying a bed-load is composed of loose grains identical in character with those transported. The material of the load is then derived from and returned to the bed and the surface of the bed is molded by the current. On the other hand, when material is transported through artificial channels, such as flumes, concrete-lined canals, and pipes, the bed is usually rigid and unyielding. In such a case, flume-traction occurs. Under like conditions of slope, discharge, and character of debris, flume-traction gives a higher bed-load than stream-traction; also larger grains can be transported.

The relation between the tractive force, velocity, and hydraulic radius can be formulated. The tractive force is

$$T = wRS \tag{16}$$

in lb ft^{-2}. According to the Manning formula

$$V = (1.486/n)\, R^{2/3}\, S^{1/2} = KR^{2/3}\, S^{1/2} \tag{17}$$

in which n is the coefficient of roughness. Substitution of the Manning formula into (16) yields

$$T = wV^2/K^2R^{1/3} \tag{18}$$

according to which the tractive force varies directly as the square of the mean velocity and inversely as the cube root of the hydraulic radius. If the Forchheimer formula, $V = \lambda R^{3/4} S^{1/2}$, commonly used in Europe, is employed, there results

$$T = wV^2/(\lambda^2 \sqrt{R}) \tag{19}$$

which Forchheimer [10b, p. 537] states has been verified experimentally by Engels [20]. In formula (19) λ corresponds to K in (18). Since the Chezy flow-formula is deduced by assuming that the tractive force is proportional to the square of the mean velocity, it is evident that equations (18) and (19) are merely different ways of expressing this relationship. When the bed-material is at rest and the flow is uniform, the tractive force is equal to the resistance offered by the wetted perimeter. As the discharge is increased, a critical flow is reached at which the bed-material just begins to move. From now on, only a part of the tractive force is used to overcome the resistance of the perimeter; the rest serves to transport material. This condition is reflected in the abrupt change in value of the roughness-coefficient that occurs when the bed begins to shift [21].

K and λ in (18) and (19), respectively, have lower values when the bed is in motion than when it is at rest, that is, the actual roughness is greater.

Often the tractive force is taken to be wd_aS, where d_a is the mean depth of flow. It must

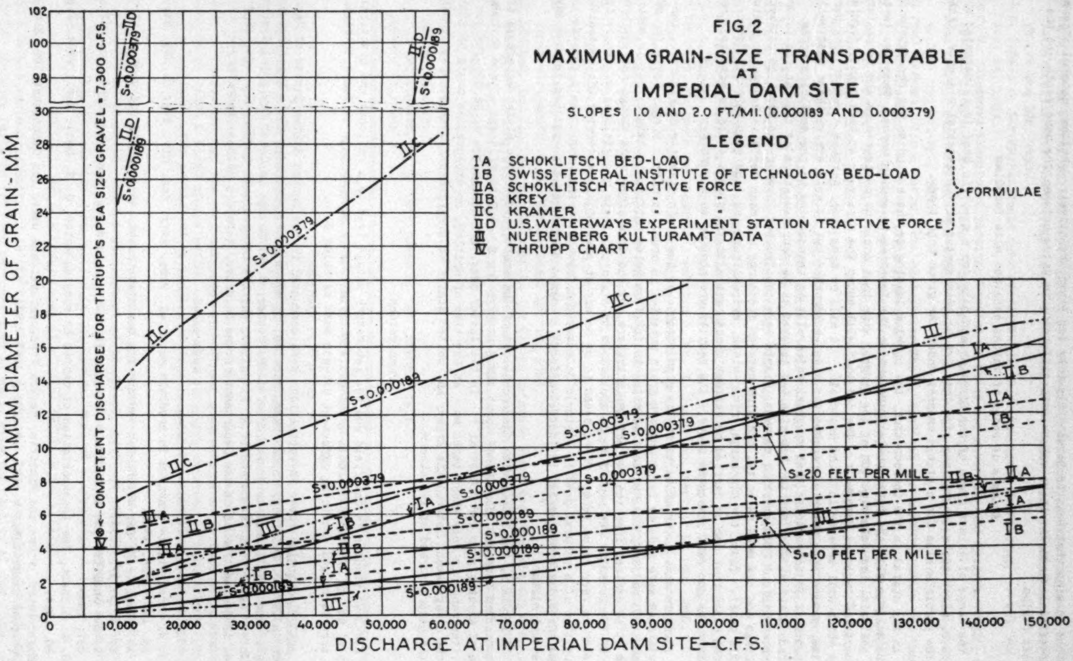

FIG. 2

MAXIMUM GRAIN-SIZE TRANSPORTABLE
AT
IMPERIAL DAM SITE

SLOPES 1.0 AND 2.0 FT./MI. (0.000189 AND 0.000379) be borne in mind that this is permissible only for broad, relatively shallow, natural streams. In artificial channels, there may be much difference in value between the mean depth and the hydraulic radius.

Example of range of values obtained with formulas

The range of values given by the formulas and data for a specific case is illustrated by Figure 2, which shows the maximum size that can be transported at the Imperial Dam site, that is, the particle-size for a stable channel under the given conditions.

As was stated in the introduction, the problem leading to these studies was the determination of the maximum size the river could transport to the Imperial Diversion Works. This is, in the last analysis, the determination of the largest size that could be delivered to the backwater limit of the Imperial Reservoir. The bed-load will enter the Reservoir at this point, forming a delta which will advance into the Reservoir. It will be some time, perhaps a rather long period of time, before this material reaches the canal-headworks; but it will arrive there eventually and hence it is taken to be that material which will be transported to the desilting works. The Colorado River at the Imperial Dam site was assumed to be representative of that at the future backwater limit. From existing records, charts were constructed showing the relation between the discharge and the mean velocity, and also between discharge and mean depth (= hydraulic radius, in this case). Thus, the discharge, river-width, hydraulic radius, and mean velocity known, the maximum sizes that can be carried by various discharges with two slopes could be computed from the formulas and data presented above The results are plotted on Figure 2.

There is some uncertainty as to the significance of the grain-diameter on Figure 2, for all computations were made as for a uniform-grain material in order to have a single basis for comparison. To be sure, the bed-load material is far from being uniform in nature, but in most cases it is derived from the bed and is, therefore, of the same size-range though not uniform. Some of the formulas are stated to be applicable to mixtures, their use yielding an "equivalent" diameter, a very vague term. There seems to be no way at present of expressing the mechanical composition of a natural sand in a simple mathematical form. All that can be said for the use of the uniform-grain diameter is that it affords a common measure of size related in some way to the actual mixture.

On Figure 2, the lines, with the exceptions of the Kramer and United States Waterways Experiment Station formulas, form bands about three mm high for $S = 1.0$ ft mi^{-1} and with a maximum range of about six mm for 2.0 ft mi^{-1}. In the latter case, for discharges of 90,000 ft^3 sec^{-1} or less, the range is only about three mm. At the time of writing, no explanation could be found for the disagreement between the Kramer and United States Waterways Experiment Station formulas and the general trend of the others.

Conclusions

Bed-load studies in the field and the laboratory should lead to a rational and practical basis of design of stable channels in erodible material. This paper brings evidence in Figure 2 of a surprising and promising agreement between most existing data.

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THE VERTICAL DISTRIBUTION OF VELOCITY IN WIDE RIVERS

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The theory of turbulent flow proposed by Osborne Reynolds and developed by Prandtl, von Karman, and G. I. Taylor has been shown to agree closely with measurements of friction-losses and velocity-distribution in pipes and along flat plates. Certain recent theoretical work by Taylor [see 1 of references at end of paper] and von Karman [2] indicates that the theory is in process of refinement but the good agreement with direct observations shows that as it stands it represents at least a first approximation of the true situation existing in a turbulent flow without a free surface. The problem to be considered here is whether it can be applied to open-channel flow as well.

Turbulent flow in pipes--A number of papers summarizing the present theory of turbulent flow have appeared recently [3] and the development of the final equations need not be given here. Starting from the assumption of a local similarity of the flow-pattern, von Karman obtains as the equation for the velocity-distribution in the central core of a long pipe

$$(U - u)/\sqrt{\tau_0/\rho} = (1/K) \left\{\log_e [1 - \sqrt{1 - (z/D)}] + \sqrt{1 - (z/D)}\right\} \tag{1}$$

Here, U is the maximum velocity, u is the velocity at distance z from the walls, D is the radius, τ_0 is the tractive force of friction per unit-area of wall, ρ is the density of the fluid, and K is a universal constant having a value between 0.38 and 0.40 for fluids in neutral equilibrium. This equation is in good agreement with experiment. It does not include either the viscosity of the fluid or the roughness of the boundaries and furthermore gives velocity-differences rather than absolute values.

The experiments of Nikuradse [4] on the friction-losses in pipes artificially roughened with uniform-sand grains showed that in the region of fully developed turbulence, that is, where the friction-coefficient is constant, the velocity-distribution near the solid boundaries but outside of the laminar sublayer can be represented by the equation

$$u = \sqrt{\tau_0/\rho}\,[2.5 \log_e (z/k) + 8.5] \qquad (2)$$

Here, the constant 2.5 corresponds to $K = 0.40$. The quantity k is the size of the grains composing the roughness. Equation (2) gives the absolute magnitude of the velocity but only for fully developed turbulent flow within a short distance from the boundary.

The quantitative definition of an hydraulically rough surface (surface producing fully developed turbulent flow) as given by von Karman is that

$$k\,\sqrt{\tau_0/\rho}/v > 60 \qquad (3)$$

This definition is framed in terms of the granular roughness used by Nikuradse. Hydraulically, surfaces are rough or smooth only in relation to an existing flow and not in an absolute sense.

Application to wide rivers--In a wide river-channel of fairly regular cross-section and bottom-slope, the component of the gravitational force must be balanced by a frictional drag and this drag must increase from the surface to the bottom. Under usual conditions, the force exerted by the air is negligible and, if the river is wide, the traction on each unit-area of bed must equal the component of the weight of fluid above it. Furthermore, the same reasoning applies to the traction at any distance z above the bed and therefore the traction increases linearly from zero at the surface to a maximum at the bed. This relationship may be expressed as

$$\tau = \tau_0\,[1 - (z/D)] \qquad (4)$$

Here, τ is the tractive force per unit-area at a distance z from the bed.

In a circular pipe, the tractive force increases linearly from the center to the walls exactly in accordance with equation [4], if D represents the radius. It appears then that equation (1) should apply to open channels provided that the conditions there do not violate other basic conditions assumed in developing the theory.

The turbulence-theory is built upon the concept of the transfer of momentum from layer to layer by transverse-movements of small masses of fluid. It is evident that such movements must be restrained by the presence of a solid boundary and in fact the theory indicates that near a boundary the transverse-distance moved is proportional to the distance z. In a pipe, the radial movement must be small near the wall where the tractive force is a maximum, but there is no restraint at the center where the tractive force is zero. In an open channel, the conditions near the bed should be the same as near a pipe-wall, but at the surface the turbulence is also restrained and this constitutes an essential difference between the two types of flow. If attention is confined to the region near the bed, the equation for the distribution of velocity in pipes should apply to open channels. In order to eliminate the maximum velocity from equation (1), consider two points at distances z_1 and z_2 from the boundary and write the corresponding equations

$$U - u_1 = \sqrt{\tau_0/\rho K^2}\; F\,(z_1/D)$$

$$U - u_2 = \sqrt{\tau_0/\rho K^2}\; F\,(z_2/D)$$

$$F(z/D) = \log_e\,[1 - \sqrt{1 - (z/D)}] + \sqrt{1 - (z/D)}$$

Subtracting the second equation from the first

$$u_2 - u_1 = \sqrt{\tau_0/\rho K^2}\,[F\,(z_1/D) - F\,(z_2/D)] \qquad (5)$$

Provided that the points considered are sufficiently close to the bed as not to be influenced by the free surface, equation (5) should represent the velocity-distribution and from a measured velocity-gradient it should be possible to compute τ_0, the tractive force on the bed.

Equation (2) is based on the assumption that the tractive force is constant and therefore is valid only for a short distance from the bed. However, with aid of equation (5) it should be possible to project the velocity-distribution down from some measured point, z_1, to a distance from the bed sufficiently small that equation (2) may be applied. Taking this point as $z = mD$, the pair of equations become

$$u_1 - u_m = \sqrt{\tau_0/\rho K^2}\,[F\,(z_1/D) - F\,(m)]$$

$$u_m = \sqrt{\tau_0/\rho}\,[2.5 \log_e (mD/k) + 8.5]$$

Solving for k, the size of the granular roughness

$$k = mDe^{[3.4 + F(z_1/D) - F(m) - u_1/\sqrt{\tau_0/\rho K^2}]} \qquad (6)$$

From the velocity u measured at a point z near the bed, it is possible to compute the effective roughness of the bed in terms of a granular roughness.

The velocity-distribution data used later on does not include direct measurements of the slope from which τ_0 might be computed and it is necessary to devise other ways of checking the correspondence between theory and observation. One method is to compute the value of n in Manning's equation which is transformed for the purpose as follows:

$$\tau_0 = wDS \qquad (7)$$

$$V = (1.49/n)\, D^{2/3}\, S^{1/2} \qquad (8)$$

Here D is the depth, S the slope of the energy-line, V is the mean velocity, and n is a factor dependent on roughness. Substituting S from equation (7) in equation (8) and solving for n gives

$$n = 1.49\, D^{1/6} \tau_0{}^{1/2}/w^{1/2}\, V \qquad (9)$$

Field-data--An unusually complete set of velocity-measurements were made in the Mississippi River in 1879 by A. Mackenzie [5] of the United States Engineers. These data were obtained by means of six current-meters attached to a shaft and recording simultaneously on a chronograph. Velocities were computed for each meter during each minute and then the average was taken over the whole period of observation. Such average values correspond to the average velocity of the turbulence-theory and should agree with equation (5) at points near the bottom, if the theory is valid. Unfortunately supplementary data on surface-slope and size of sand were not published in the report and the original records appear to have been lost.

According to the theory of turbulent flow, the following conditions should exist:

(a) Any set of simultaneous readings taken over a short interval of time may show a very irregular velocity-distribution.
(b) As the time-interval increases over which the velocity-measurements are averaged, the curve of average velocities should conform more closely to equation (5).
(c) Different pairs of points on the same average curve taken near the bottom should yield the same value of τ_0.
(d) Provided that the bed is hydraulically rough as indicated by equation (3), the values of the roughness-coefficient k from equation (6) should fall between the actual sand-size and the size of the ripples forming the bed.

Analysis of the data of Mackenzie by E. C. Yerby (unpublished thesis, University of California, December, 1936) showed good agreement with the theory. The method of comparison was as follows:

(1) From the averaged velocity-curves three pairs of points were taken below mid-depth and from each pair the tractive force τ_0 was computed from equation (5).
(2) The averaged values of τ_0 were used in equation (5) to compute a velocity-curve which passed through the lowest measured point.
(3) Values of k were then computed from equation (6) with $mD = 0.01$ foot.
(4) The average velocity was obtained from the measured velocity-curve and inserted in equation (9) to give n.

Tractive forces computed from pairs of points on the same velocity-curve were in good agreement if all points were below 0.5 D. The velocity-curves, computed from the average τ_0 and equation (5) and drawn through the lowest observed point, showed good agreement with the measurements. There was no general tendency for the theoretical curve to be either steeper or flatter and in most instances the theoretical curve could have been taken as the best line through the points with only a slight adjustment horizontally. Just two measured velocity-curves out of 24 showed the maximum velocity below the surface. Such exceptions represent a basic deviation from equation (5), which is really not applicable near the surface, but in wide channels depression of the thread of maximum velocity appears not to be common.

The other quantities computed from the measured velocity-curves are listed in Table 1. The values of n are between 0.018 and 0.042 which is in the range generally recommended for rivers. The values of k range from 0.0014 to 0.98 foot which is reasonable for the bed of a large river. Extensive bed-sampling has been carried only as far up the river as Cairo at which point the samples show median diameters between 0.0012 and 0.007 foot. The computed values of n and k were found to follow the equation $n = 0.049\ k^{1/6}$ which is remarkably close to the equation of Strickler which is $n = 0.039\ k^{1/6}$.

Table 1

Curve	Depth	Mean velocity	τ_0	n	k
	feet	feet/sec	lbs/sq.ft.		feet
A	19.5	1.76	.0458	.0376	.152
B	21.25	1.94	.0688	.0423	.690
C	11.5	1.86	.0281	.0254	.0218
D	11.0	1.94	.0253	.0230	.0144
E	13.2	2.46	.0881	.0340	.114
F	13.2	2.55	.0470	.0259	.0193
G	12.6	2.42	.0278	.0197	.0286
H	13.0	2.51	.0241	.0178	.0017
I	13.0	2.46	.0600	.0288	.153
J	13.5	2.48	.0241	.0179	.00144
K	13.7	2.46	.0516	.0269	.0285
L	21.6	2.17	.0392	.0288	.0402
M	21.6	2.14	.0596	.0343	.112
N'	21.6	2.18	.0655	.0369	.983
N	21.6	2.19	.0478	.0315	.126
O	21.6	2.14	.0456	.0313	.0724
P	21.6	2.16	.0415	.0297	.0529
Q	21.6	2.11	.0539	.0346	.126
R	21.6	2.14	.0584	.0357	.132
S	21.6	2.14	.0361	.0280	.0390
T	21.6	2.17	.0392	.0269	.0294
U	21.7	2.13	.0344	.0274	.0335
V	27.6	1.815	.0120	.0198	.149
W	27.6	1.786	.0281	.0306	.0193

Conclusion--Data available for comparison with the theoretical velocity-distribution are in nearly every instance incomplete. The data of Mackenzie are better than average for this purpose because each velocity-curve is an average over a long time. The reasonableness of the results obtained at least points to the existing theory as a suitable basis for additional investigations and it is to be hoped that someone will eventually find it possible to obtain for some river a complete set of simultaneous hydraulic data.

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[1] G. I. Taylor, Proc. R. Soc. London, v. 151 A, October, 1935.

[2] Th. von Karman, The fundamentals of the statistical theory of turbulence, J. Aeronautical Sci., v. 4, No. 4, February 1937.

[3] Th. von Karman, Turbulence and skin-friction, J. Aeronautical Sci., v. 1, No. 1, January 1934.

[4] J. Nikuradse, V.D.I. Forschungshaft 361, Berlin, 1933.

[5] A. Mackenzie, Report on current-meter observations in the Mississippi River, near Burlington, Iowa, during the month of October, 1879, Washington, Gov. Printing Office, 1884.

University of California,
Berkeley, California

A COMPREHENSIVE STUDY OF THE RAINFALL ON THE SUSQUEHANNA VALLEY

Carroll F. Merriam

In the very short time that can be devoted by the Section of Hydrology to a subject of rather local interest, it is not fitting to attempt to cover more than the general phases of this study, which started out to be worthy of its title. It was not long before it was found that "comprehensive" should be changed to "somewhat comprehensive," and, like many endeavors of this kind, the more we know, the more we know that the proportion of what we know to what is to be known is much less than we thought at the outset. As a result, it would have been appropriate to alter the title still further by inserting "rainfall-records" in contradistinction to "rainfall."

The Susquehanna Valley was selected for intensive study, in the first place because of the vital interest to the power-developments on the River, and second, because a number of years had passed since a somewhat similar study had been reported by the Hydraulic Power Committee of the Pennsylvania Electric Association. It was desirable to see whether the additional years of record and the application of certain refinements of method would substantially alter the rainfall-map published at that time (1930). Furthermore, it was decided to test the practicality of a program of analysis that we had been asked to outline for a general review of all rainfall- and runoff-records throughout the country, and to judge whether or not our estimate of time required was reasonable.

It is not necessary here to deal with specific results because the members of the Section as a whole are little interested in knowing that certain rainfall-records in Pennsylvania stand the test better than others, and that many records may actually be misleading as a guide in estimating the true average rainfall that may be expected in years to come.

Except to review briefly certain salient facts, it is not necessary to describe the method in detail as that has already been covered in printed reports. Among these are the following:

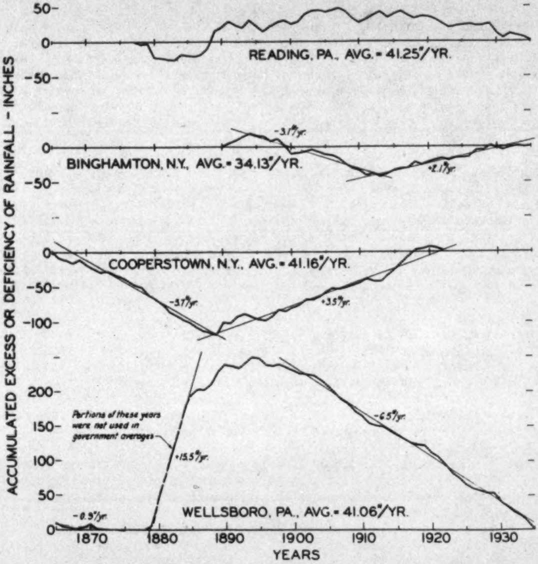
Report of Committee on Runoff, Section of Hydrology, Amer. Geophys. Union, prepared by L. K. Sherman and R. E. Horton for presentation at the Lisbon Assembly of the International Union of Geodesy and Geophysics in 1933 (photo-offset copy of portion pertaining to inconsistencies may be had on application to author of this paper).
Pennsylvania Electric Association, Report of Hydraulic Power Committee, 1929, pp. 26-29.
Pennsylvania Electric Association, Report of Hydraulic Power Committee, 1930, pp. 22-31.
National Electric Light Association, Pub. 115, Forecasting water-supply: Detection of inconsistencies in long-term rainfall- and runoff-records with suggestions for their correction.
(The last three are out of print, but photostat copies may be ordered from the United Engineering Societies Library, 29 West 39th Street, New York, N. Y.)

These reports describe three tests for consistency. The first test is essentially the progressive accumulation of departures from the arithmetic mean of a series of numbers, representing, for example, annual rainfall, taken in chronological order. The process is simply to start with zero, add the first one of the series, subtract the mean, strike a subtotal, add the second, subtract again the mean and strike the second subtotal, and so on to the end. The subtotals are then plotted against time, the final ordinate being zero, for the reason that in the end exactly as much had been subtracted as added. Now if a series of numbers should vary about some fixed value purely at random and if there were sufficient observations, the resulting plot, although irregular, would have a definite trend. If this fixed value is a constant for the entire series, the trend will be horizontal, or nearly so, but if there is a definite change at any point, there will be a distinct change in slopes of the portions of the curve before and after.

Unfortunately this effect is all too clearly demonstrated by the majority of long rainfall-records. As a rule, it is necessary only that they extend over a sufficiently long period that the accidental grouping of wet and dry years does not obscure the major changes in average. Not being able to ascribe sudden changes in average rainfall thus indicated by abrupt breaks in the general trend to natural causes, the most plausible explanation seems to be an artificial alteration in the condition of observation.

Figure 1 illustrates a few cases that are somewhat typical. For example, the record at Cooperstown, New York, from 1865 to 1923, shows plainly that in 1889 or thereabouts there was a very decided change in the mean from 5.7 inches less than the average for the entire period to 3.5 inches above. Binghamton, New York, shows such a change amounting to 5.2 inches which occurred at a time which is coincident with the moving of the gage from the roof of the observatory

FIG. 1
FIRST TEST OF SEVERAL TYPICAL RAINFALL-RECORDS



to the lawn. It should be emphasized that, as mentioned before, this condition is rather typical of all of the longer records that we have investigated. Wellsboro is included here as a curiosity, and fortunately few similar ones were found. The mean for the years between 1878 and 1885 was so extreme that there is a note in the Government Bulletin stating that certain months in these years were omitted in determining the official mean. However, the striking feature is the gradual curve, or rounding after 1885, which could be interpreted to mean a progressive alteration of the average. In cases where this effect had been noticed previously, it had been ascribed to slow changes in exposure such as might be caused by growing trees. Why the change should be so extreme is still a mystery, but at least it may be stated that the records, say until 1900, have little or no value in determining the true mean, and to include them in a blind average would certainly be misleading.

Reading shows about what can be expected from a record that may be considered to pass the first test and subject to further examination by the second. It is not as straight as would be hoped for, as there is a slight tendency to curve gradually as though the mean rainfall were slowly decreasing. However, this first test should be considered only as a sort of rough screen to detect the more flagrant defects which may be confirmed by the second.

The second test is essentially the plotting accumulatively of one set of data against another. In the form used in this study the criterion was made up of a composite of some 30 or 40 rainfall-records which either in whole or in part appeared satisfactory in the first test. In fact, the principal use of the first test was to select the records, or portions of records, that could be used for building up this composite, known as the standard pattern. The accumulated values for the successive years are plotted on the scale of abscissae in Figure 2. Again but a few typical examples are shown of the 212 records that were examined, the same four being selected so that the relation between the first and the second test could be easily seen.

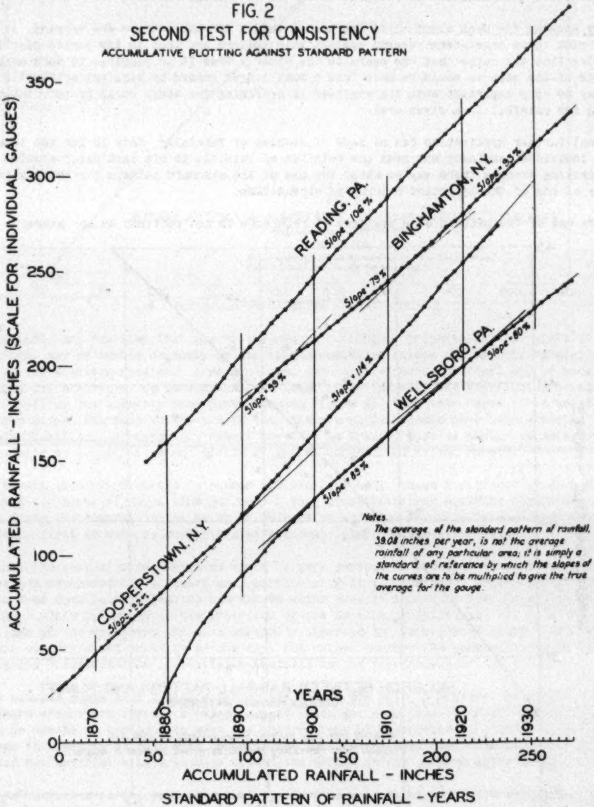
Cooperstown shows the same break as in the first test except that by plotting against a standard, which itself has corresponding accidental variations caused by periods of general wetness and dryness, the humps and the valleys which somewhat obscure the break in the first test are almost entirely smoothed out. Consequently, any real change in slope of the curve becomes much more distinct. In like manner Binghamton becomes clearly a Z, thus showing a second break not fully evident in the first test. Wellsboro shows until 1900 a gradual curving toward the trend that it follows subsequently, but furthermore this more exacting test discloses an additional break in 1920. Reading is somewhat typical of the very few really long records that showed any resemblance to consistency for the entire period of record. Out of 212 records studied, approximately 100 were long enough to show whether a break did exist or not. Out of these, the ones similar to Reading could easily be counted on the fingers of one hand, and in the rest 140 breaks were located.

It should be noticed that the slope of these curves expresses the ratio that the mean for any period of time bears to the mean for the pattern. As this latter can easily be found either

FIG. 2

SECOND TEST FOR CONSISTENCY

ACCUMULATIVE PLOTTING AGAINST STANDARD PATTERN



Notes.
The average of the standard pattern of rainfall, 39.08 inches per year, is not the average rainfall of any particular area; it is simply a standard of reference by which the slopes of the curves are to be multiplied to give the true average for the gauge.

arithmetically or by least squares, if greater refinement should be desired, then these slopes can be converted to inches per year. The differences in slope may also be expressed as changes in catchment in inches per year. It is possible that by knowing the amount of the change in catchment and the approximate time, some valuable information can be secured concerning the care that is necessary in observing rainfall and the probable accuracy of the records.

The question may be raised whether, when there are two distinct slopes at different periods, there is any reason to suppose that one is more correct than the other. All that can be said on this point is that with improvement in technique it would be supposed that the later would be more correct than the earlier. At least it would be possible to check a current record to see if there were any defect in the exposure. A further test is to plot a rainfall-map to determine which of the two satisfies more closely the records from surrounding gages.

The next question is the use to which this test can be put beyond that of bringing to light the apparent changes in the mean and the amount of difference. The application that comes first to mind is the determination of reliable estimates of average rainfall from short-term records.

By knowing the mean about which the annual values for the pattern are varying, it is possible to plot these short-term records against this pattern and thus in the period of relatively few years find the ratio that one bears to the other. Thus it is possible to make as good an estimate of the mean as could be made from a much longer record by straight arithmetic averaging. This may be very important when the engineer is searching for every scrap of information concerning the rainfall in a given area.

What further application can be made of studies of rainfall? This is for the imagination of the individual engineer who sees the relation of rainfall to his particular studies. However, as a striking example there may be cited the use of the standard pattern for testing the reliability of one of the important records of stream-flow.

The use of the pattern as a standard of reference is not confined by any means to rainfall

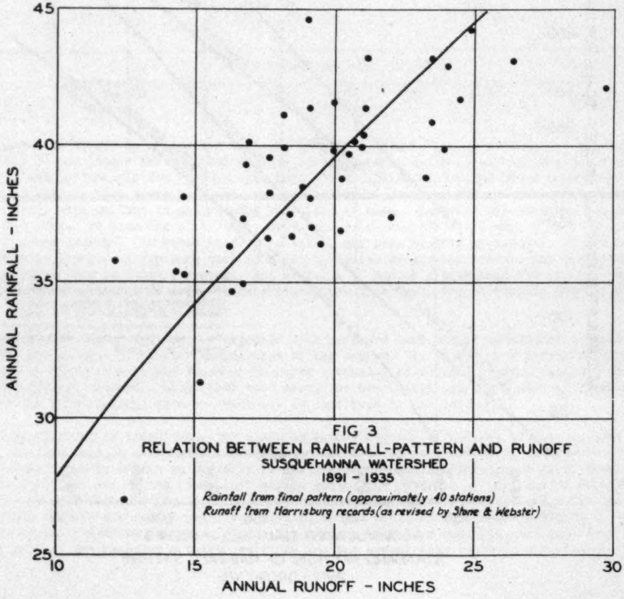
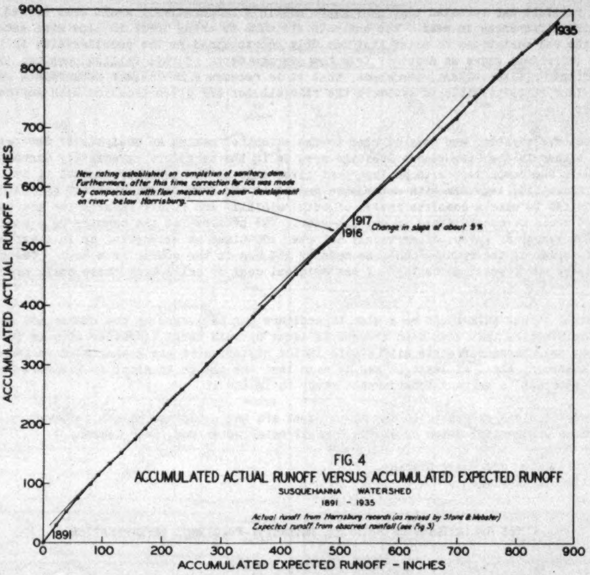


FIG 3
RELATION BETWEEN RAINFALL-PATTERN AND RUNOFF
SUSQUEHANNA WATERSHED
1891 - 1935

Rainfall from final pattern (approximately 40 stations)
Runoff from Harrisburg records (as revised by Stone & Webster)



New rating established on completion of sanitary dam. Furthermore, after this time correction for ice was made by comparison with flow measured at power-development on river below Harrisburg.

Change in slope of about 9%

FIG. 4

ACCUMULATED ACTUAL RUNOFF VERSUS ACCUMULATED EXPECTED RUNOFF

SUSQUEHANNA WATERSHED

1891 - 1935

Actual runoff from Harrisburg records (as revised by Stone & Webster)
Expected runoff from observed rainfall (see Fig 3)

alone. In fact, any function that may be assumed to be roughly proportional to rainfall, such as river-flow, may be tested directly by plotting accumulated values against the rainfall-pattern with fairly satisfactory results. A more refined and positive test, however, may be made by first taking the precaution of determining, at least approximately, the correlation between rainfall and runoff by the commonly used plot shown in Figure 3. From this curve it is possible to convert from actual rainfall to the runoff that the actual rain would have been expected to produce. This fictitious, or expected, runoff may then be treated just as though it were real, and may be compared by accumulation and plotting against accumulated actual runoff.

The result shown in Figure 4 is rather illuminating as it shows a distinct break and a very marked change in slope of about nine per cent. This break coincides with the completion of a dam which forms the control in the River at this point and also the time from which correction for ice could first be made by comparison with a power-plant on the River below.

An inconsistency of this magnitude would be very serious in the case of a stream where the total flow was impounded for ultimate use, particularly if for municipal water-supply. The revelation that such inconsistencies can and do exist even in important records points to a grave danger. This is called to the attention of the Section of Hydrology, not with any idea of placing blame on the engineers who have carefully observed and interpreted their data according to the best standards and practice of the day, but rather to show the possibilities that we now have of saving ourselves from the pitfalls that lie in the very nature of the problem.

This example shows in a striking manner how we are now able to analyze, correlate, and determine where errors are likely to exist, and at least get some idea of their extent. It would certainly be unwise to continue to make new observations with perfected and refined technique and average the results blindly with those of the past in the hope that eventually the weight of accumulated new material will gradually offset the errors in the earlier observations.

It was mentioned at the beginning that this proved a study of rainfall-records rather than rainfall. The collection of means for a large number of gages and the plotting of these on a general rainfall-map revealed that many gages within a comparatively small area showed rather surprising differences in mean. The analysis did much to bring these in line with each other, but in the end variations do exist that can only be explained as the peculiarities in the catchment of individual gages as distinct from the average depth of rain falling upon the immediate surroundings. It is evident, therefore, that it is necessary to collect data from a number of gages before it is possible to estimate the rainfall for any given location with any degree of certainty.

This investigation was only carried to the extent of making an analysis of 212 rainfall-records either in the Susquehanna Drainage-Area or in the territory immediately surrounding, together with one comparison with an important river-gage on the main stream, but it is clearly evident from this, together with experience gained in the 1930 study, that our estimate of the time required to make a complete review of both rainfall- and runoff-records for the entire watershed could be accomplished in one man-year. The problem for the country as a whole, judging by the number of gages, is certainly not over 100 times as extensive, or in other words a complete survey of the country could be made by 100 men in the course of a year. The cost would obviously be but a small percentage of the original cost of collecting these basic hydrologic data.

Whether or not this would be a wise expenditure can be judged by the number and extent of the inconsistencies that have been brought to light by this trial, together with an investigation to see how well these correlate with events in the histories of the gages, such as changes in exposure, observer, etc. At least it may be said that the change in slope on Figure 4 is sufficiently important to warrant considerable study to locate it.

[Note--Opinions expressed in the above paper are the author's and not necessarily those of the American Geophysical Union or of the Pennsylvania Water and Power Company.]

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THE RELIABILITY OF RAINFALL INTENSITY-FREQUENCY DETERMINATIONS

C. W. Thornthwaite

In studies of rainfall and runoff two distinct types of rainstorms, each having characteristic size, shape, internal structure, and behavior-patterns, must be considered. The first is of rather short duration (one to three hours), covers 1000 square miles or less, and has centers of high rainfall-intensity with rates often exceeding five inches an hour. The second type is of wide areal extent, sometimes as much as 400,000 square miles, and of several days duration, is gentle and continuous, and contributes large amounts of water to the storm-area. Not infrequently in connection with the wide-spread continuous type of rain, local areas will experience for short periods the high intensities of the first type.

The first type of rainfall is especially significant in the production of gully- and sheet-erosion and occasional local floods. The second type is significant in stimulating mass or gravity-movements of soil, such as slumping, field-slides, and caving of gully-sides and gully-heads, and is invariably the cause of major floods.

Rainstorm-morphology--Recognizing the importance of relating soil-erosion to rainfall-types, the Soil Conservation Service has established two climatic field-projects for studying rainstorm-morphology. At the Oklahoma Climatic Center 200 weather-stations, spaced about three and one-half miles apart over 2400 square miles, have been in continuous operation since January 1936. Quarter-hourly records of precipitation, and to supplement them, hourly records of temperature, wind-velocity and wind-direction, relative humidity, cloudiness, dust, and fog, have been accumulated for the entire period [see 1 of references at end of paper]. Maps showing the actual rainfall for every 15-minute interval for over a year permit a more detailed analysis of distribution and intensity of precipitation than has ever before been possible. The battery of 200 raingages is regarded as a single instrument for obtaining samples in sufficient number in different parts of each rainstorm to permit the determination of its characteristics. The second climatic field-project has 500 weather-stations, spaced approximately four miles apart, over the 8000 square miles of the Muskingum Watershed in Ohio.

Both climatic projects are well adapted to the study of local or "cold-front" types of storms, but they do not cover enough territory to sample more than a section of a general or

FIG. 1—RAINSTORM OF JUNE 30, 1936

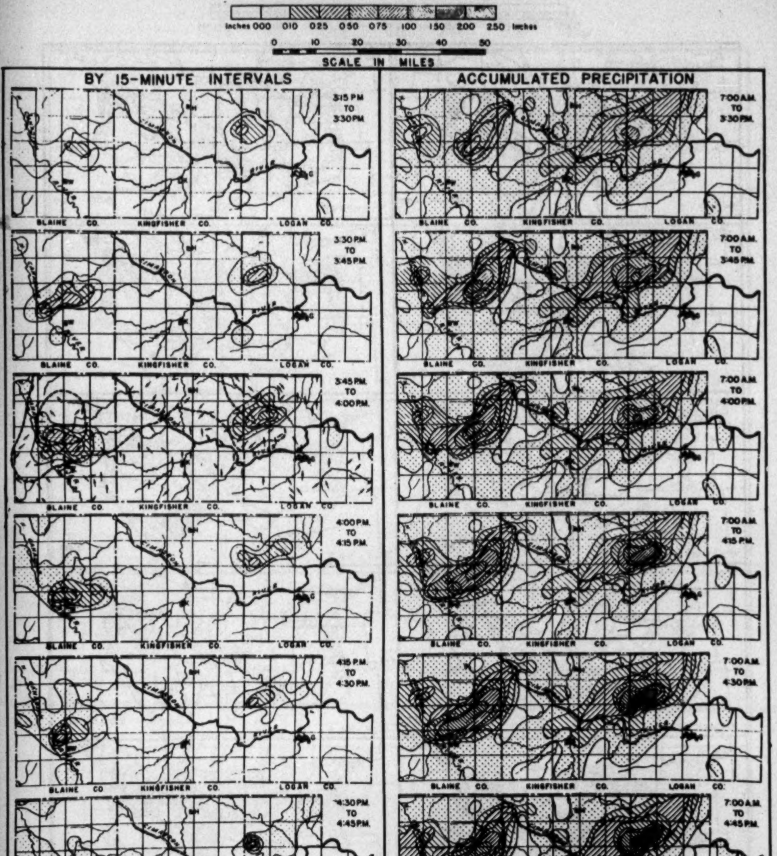

Inches 0.00 0.10 0.25 0.50 0.75 1.00 1.50 2.00 2.50 Inches
0 10 20 30 40 50
SCALE IN MILES
BY 15-MINUTE INTERVALS
ACCUMULATED PRECIPITATION
3:15 P.M. TO 3:30 P.M.
3:30 P.M. TO 3:45 P.M.
3:45 P.M. TO 4:00 P.M.
4:00 P.M. TO 4:15 P.M.
4:15 P.M. TO 4:30 P.M.
4:30 P.M. TO 4:45 P.M.
4:45 P.M. TO 5:00 P.M.
7:00 A.M. TO 3:30 P.M.
7:00 A.M. TO 3:45 P.M.
7:00 A.M. TO 4:00 P.M.
7:00 A.M. TO 4:15 P.M.
7:00 A.M. TO 4:30 P.M.
7:00 A.M. TO 4:45 P.M.
7:00 A.M. TO 5:00 P.M.
CIMARRON RIVER
BLAINE CO.
KINGFISHER CO.
LOGAN CO.

FIG. 2A—RAINSTORM OF JANUARY 20, 1937—MORNING

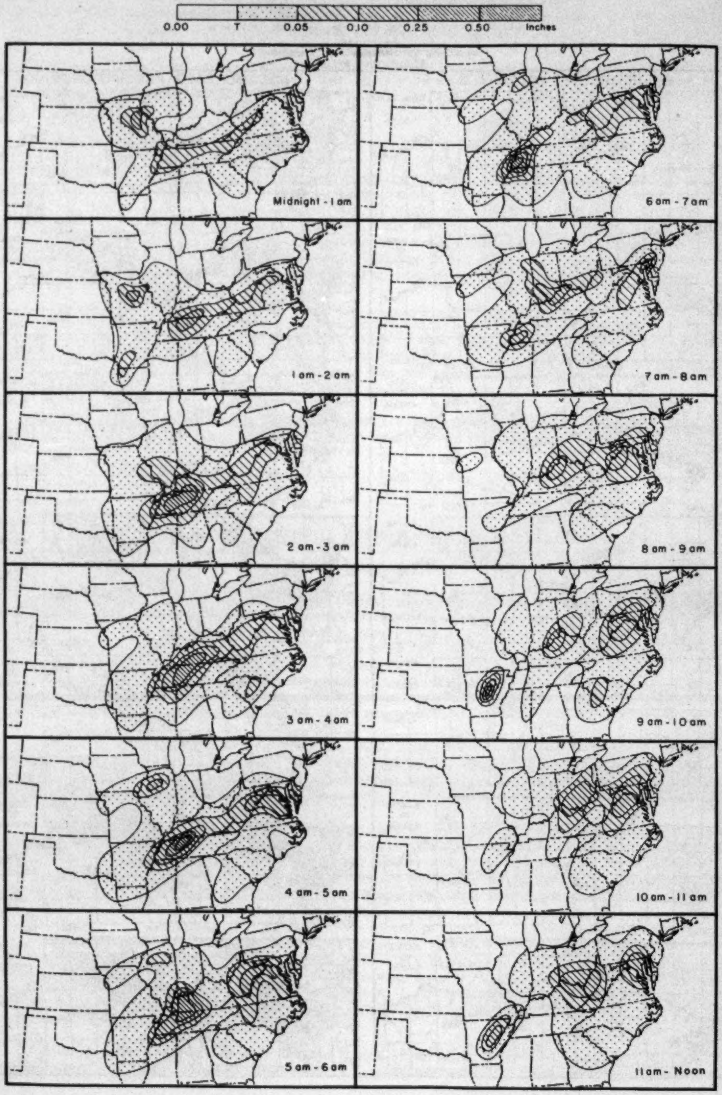
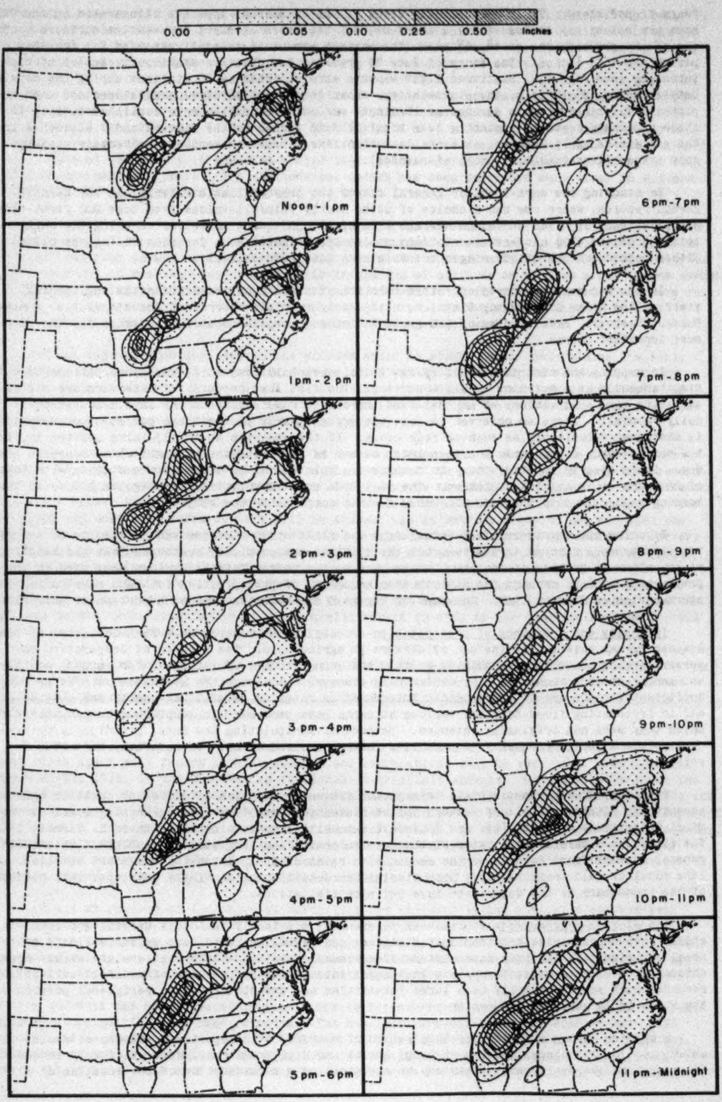

0.00
T
0.05
0.10
0.25
0.50
Inches
Midnight - 1 am
6 am - 7 am
1 am - 2 am
7 am - 8 am
2 am - 3 am
8 am - 9 am
3 am - 4 am
9 am - 10 am
4 am - 5 am
10 am - 11 am
5 am - 6 am
11 am - Noon

FIG. 2B—RAINSTORM OF JANUARY 20, 1937—AFTERNOON


0.00
T
0.05
0.10
0.25
0.50
Inches
Noon - 1 pm
6 pm - 7 pm
1 pm - 2 pm
7 pm - 8 pm
2 pm - 3 pm
8 pm - 9 pm
3 pm - 4 pm
9 pm - 10 pm
4 pm - 5 pm
10 pm - 11 pm
5 pm - 6 pm
11 pm - Midnight

"warm-front" storm. Two characteristic forms of the cold-front type are illustrated on the Oklahoma project by the storms of May 1 and June 30. The storm of May 1 crossed the northern boundary of the project-area at 4^h 45^m p.m. The maximum amount of rainfall reported for any 15-minute period was 1.54 inches. The storm of June 30 produced two distinct stationary centers of high intensity (see Fig. 1). Scattered light showers were reported by 30 stations during the morning. Between 3^h and 3^h 15^m p.m. the storm-centers shown in the series of maps developed and each reported 0.41 inches of rain during the 15-minute period. Thereafter rain continued to fall in these separated centers, amounting to a total of 2.27 inches in the western and 3.81 inches in the eastern center. However, stations less than five miles from each of the centers reported only traces (less than 0.01 inch) of rainfall.

In studying the warm-front or general storms the only available material is the Weather Bureau records, where one has a choice of using hourly rainfall-values from some 200 first-order stations, each of which serves an average area of 15,000 square miles, or of using the daily totals from the 4700 cooperative stations spaced approximately one for each 650 square miles. Either method has its disadvantages but both have been used at various times.

In the monumental reports on "Storm-rainfall of eastern United States" the engineering staff of the Miami Conservancy District, using daily rainfall-records of the cooperative Weather Bureau observers, made studies of 280 great storms and prepared distribution-maps for the 72 most important storms.

In mapping the distribution of storms it is, obviously, essential that observations be made simultaneously at a set time by all observers. The fact that cooperative observers are not required to make observations at any set time introduces considerable error into measurement of daily rainfall. Where an observer is late one day and early the next the period of observation is shortened conceivably as much as four hours. If the observer at an adjoining station is, for the same period, first early and then late, he may be reporting the rainfall of 28 hours in one day. It is clearly unsatisfactory to compare the rainfall of 20 hours at one station with that of 28 hours at an adjoining station. The fact that some observations are regularly made in the morning rather than in the late afternoon further complicates the situation.

By using the hourly rainfall-values from the first-order stations the difficulty of securing simultaneous records is overcome but the stations are so widely scattered that the sampling of the storm is grossly inadequate. Nevertheless, the hourly rainfall-values were used in the preparation of maps showing the distribution and depth of precipitation for each hour during the storm-period of January 1937. The maps of Figure 2 are selected to show a portion of this storm.

Intensity and frequency of precipitation--Precipitation-records have been collected by the Weather Bureau chiefly for the use of workers in agriculture. The reports of cooperative observers are adequate for determining monthly and annual totals of rainfall, for mapping monthly and annual distributions, and for determining averages. Although the available records are insufficient for the use of hydrologists interested in relating rainfall to runoff and stream-flow and in forecasting flood-hazards, various attempts have been made to adapt them to purposes for which they were not originally intended. Methods of manipulating the data, principally to determine the expected frequency of excessive intensities and amounts of rainfall, have been developed.

The two most important manuals on expected frequency of rains of different duration and amounts are "Storm-rainfall of eastern United States (revised)" by the engineering staff of the Miami Conservancy District [2], and "Rainfall intensity-frequency data" by David L. Yarnell [3]. The first deals chiefly with rains of moderate intensity and long duration and great extent (the general or warm-front rains) and the second with rains of great intensity and short duration (the local or cold-front rains). Both studies are detailed and carefully developed but, because of the inadequacy of the data, both have definite limitations.

The station-year method--It has been pointed out previously that both general and local storms have characteristic patterns of structure and migration; both have definite limits of areal distribution; and both have centers of maximum intensity. Where stations are evenly spaced throughout a storm-area it is obvious that small intensities and amounts of rainfall will be recorded much more frequently than large intensities and amounts since the peripheral portion of the storm is larger than its center.

A station having a reasonably long record of rainfall will report many storms of small amount and low frequency, and few of large amount and high frequency. Records of very intense falls will be extremely rare. This may be explained by a consideration of the location of individual storms with reference to the station. Since a storm-center is comparatively small it is more probable that some portion of the periphery rather than the center itself will fall on the station. Storms vary in size also, and this variation helps to explain the frequency-distribution of recorded amounts of precipitation at an individual station.

For many years hydrologists have attempted to obtain more accurate determinations of precipitation intensity-frequency by combining the records from a group of adjoining stations to make a single long record. If ten nearby stations each have a 30-year record, there would be a station-year record of 300 years and if a particular excessive rain occurred once at one station and at none of the others it would be stated that this excessive rain could be expected at each station once each 300 years. The station-year method has been described many times in engineering literature and should be well known.

The station-year method of combining rainfall-records from a number of stations to build up a single composite record of great length assumes a random distribution of storms in a uniform area and requires either an absolute identity in size and structure of storms or a uniformity in their sequence of frequency and a uniformity in spacing of stations as well as a sufficient number of stations to assure that all storm-centers were recorded. If all of these conditions were fulfilled, a composite of short records from a number of stations would yield exactly the same storm intensity-frequency values as a long record from a single station.

In the case of identical storms the problem would be simply one of determining the size, structure, and frequency of the standard storm. The relative frequency of values of varying amounts would be directly proportional to the area in the storm receiving these amounts. The greater the length of the composite record, the greater would be the probability that some station had recorded the exact center of highest intensity.

In so far as storms vary in size and in frequency from year to year and as stations are irregular in distribution, the station-year method will fail to yield a reliable long-time record. With an irregular spacing of stations there will always be the danger that some are concentrated in such a manner that a certain section of a storm would be sampled more than its proper number of times and that some storm-centers will be missed. As an extreme example, suppose that two gages stand side by side and both always record precisely the same amount of rainfall for every storm. It is obvious that these two gages would yield no more information than a single gage and that the combined record would mean no more than an arbitrary doubling of the frequencies of a single gage. If the records for these two gages were both included in the station-year composite, it would tend to bias the result in favor of the rainfall-values which chanced to occur at that point. Any irregularity of spacing will result in bias to the combined records for all storms which affect more than one station.

The degree of success of the station-year method in producing a reliable long record for an area depends on the amount of correlation between stations. As the correlation increases the utility of the method diminishes; in the illustration cited above with correlation complete the combination of records would accomplish nothing.

In the very large general storms rainfall is so uniform over large areas that stations several miles apart will record similar amounts and correlations will be very high. The storm of March 21-27, 1913, in the Ohio Valley furnishes an excellent example. On pages 64 to 66 in the revised edition of "Storm-rainfall of eastern United States" the 16 greatest rainfall-records for one to six days at the stations in quadrangle 9-E are tabulated. The storm of March 1913 supplied 11 of the 16 three-day rainfall-records, 12 four-day records, 13 five-day records, and 11 six-day records. All 25 stations in operation in the quadrangle in 1913 reported excessive five-day rainfall for the March storm. This indicates that for this particular storm the correlation among stations is very high, as it would necessarily be in all great storms.

If all 25 records of the storm of March 1913 are included in the composite station-year record, the result would indicate that the least rainfall recorded at any station would be exceeded 25 times during the 1250-year period represented by the combined station-records. This is equivalent to saying that a storm of this sort would occur on the average once in every 50 years with the maximum values occurring successively at each of the 25 stations.

A storm of the magnitude of that of March 1913 occurred only once in the 50 years (approximately) since rainfall has been recorded. The heaviest five-day rainfall recorded was 11.37 inches. If we assume that a storm of this sort is repeated every 50 years on the average and that each of the 25 stations has an equal chance of experiencing the maximum rainfall of the storm, it is clear that each station might expect to have a five-day rainfall of 11.37 inches once every 1250 years. However, the fact that this storm did occur once during the 50-year period is no indication that a similar one will occur every 50 years. In fact, there is nothing in the record which will reveal anything about the frequency of such storms. There is no way of knowing that they occur, for example, more than once every 1000 years, in which case any station might expect a five-day rainfall of 11.37 inches only once in 25,000 years, provided these 25 stations are close enough together so that the center of every storm was recorded.

The real value of the station-year method emerges when storms of small areal extent are involved. A composite station-year record of these storms which are recorded only at single stations is in effect a record of the number of such storms which occurred in the area. Assuming a random distribution of storms it is reasonable to expect that, in the number of years represented by the combined records, any one station would experience the same number of storms as had been recorded in the entire area. This result will, of course, be in error in so far as the distribution of stations is such as to fail to record all small storms which occur in the area. The method assumes that the same frequency of small storms actually recorded in the area will be experienced in a long period. Although undemonstrated, this is not an unreasonable assumption. Thus, except for errors due to inadequacies in spacing of stations, the station-year method could be expected to yield valid results when the storms involved are so small that there is no correlation between stations.

The station-year method as now employed consolidates records of storms of all sizes. To the extent that large storms are involved, the reliability of the results is impaired. There is no immediate prospect that the method can be revised to permit a determination of the expected frequency of large storms.

It is conceivable that current developments in air-mass meteorology may supply methods and information which will permit the determination, on theoretical grounds, of the maximum storm to be expected in an area. There is, however, little likelihood that it will be possible to determine the statistical probability of the recurrence of the meteorological forces combined in such a way as to produce this maximum storm. Thus storm-frequencies would still remain indeterminate.

Rainfall intensity-frequency data--Yarnell, in "Rainfall intensity-frequency data," published 56 maps for the United States in which he shows the maximum amount of rainfall in 5, 10, 15, 30, 60, and 120 minutes which may be expected in 2, 5, 10, 25, 50, and 100 years and the maximum 4-, 8-, 16-, and 24-hour rainfall which may be expected in 5, 10, 25, 50, and 100 years. The isohyetal interval varies from 0.05 inch on the five-minute maps to 0.50 inch on the 24-hour maps. In making the maps for durations up to and including two hours the records from the automatic gages of the 211 first-order Weather Bureau stations were employed. For the 24-hour maps the familiar station-year method of consolidating records from cooperative Weather Bureau stations was employed. The maps for rains of 4, 8, and 16 hours' duration were made by interpolating from values on the maps of short durations and those for 24 hours.

In a personal letter Mr. Yarnell explained that the reason his 24-hour maps do not agree with those of the Miami Conservancy District is that he actually counted all the storms above a certain minimum, usually from 1.50 to 3.00 inches, where the District engineers employed only those storms equaling or exceeding a certain percentage of the normal annual rainfall at the point considered.

Short duration and high intensities of rainfall are, from the nature of their occurrence, limited in their areal extent. They are associated with cold-front rains in which convectional instability is the activating force. In these storms rain rarely falls simultaneously on an area of more than 1000 to 2000 square miles in extent and the center of highest intensity is rarely greater than 25 square miles.

In the United States, where 211 automatic gages serve more than 3,000,000 square miles, with nearly 15,000 square miles per gage, the probability that the center of the storm of maximum intensity would be recorded in any gage is very slight. For the United States the probability is about one in 600, for the Great Plains it is one in 1000, and for the western states it is even less. In other words, there is about one chance in 600 that a particular storm-center having an area of 25 square miles would fall in such a way as to be recorded on a gage in the center of an area of 15,000 square miles. In Yarnell's computations, therefore, there is only about one chance in 600 that he actually has a record of the greatest intensities in any given area. This situation would not be improved in any way by an increased length of record. If records for 500 years were available, the probability that the storm of greatest intensity had been recorded would still be the same.

The only way in which greater accuracy can be obtained with Yarnell's method will be through the establishment of a closer network of stations supplying automatic records. If every cooperative Weather Bureau observer had an automatic gage, the probability of recording the storm-center of greatest intensity would be about one in 40 for the United States as a whole and one in 25 for certain sections in the East. That is, the center of one out of every 40 storms would occur in such a way as to be recorded.

It is not to be inferred, however, that a long record is not essential in the determination of rainfall intensity-frequencies. Each added year of observation increases the probability of recording a rain of *extreme* intensity, even though it does not increase the probability of recording the rain of *greatest* intensity.

It can be shown on the basis of probability that increasing the length of record at a weather-station increases the probability that a storm of any given intensity will be recorded at a station.

Assuming that there are ten stations in an area distributed in such a way that the centers of all storms of given size and intensity will be recorded at one station and at only one, the chances that one such storm-center *will* hit a particular station are one in ten and that it will *not* are nine in ten. Each storm of this type will have the same chances of hitting and of not hitting the specified station. If a series of n number of storms followed each other in the area the chances that one would hit the particular station, in other words, that it would appear in the station-record, are $1-(9/10)^n$. For ten storms entering the area the chances that any one would be recorded at a particular station are $1-(9/10)^{10}$ or 65 per cent.

For example, the probability that a storm to be expected at a station on the average once in ten years will be actually found in a given 10-year record is only 65 per cent, whereas the probability that it will be found in any 20-year record is 88 per cent and in a 50-year record 99 per cent. Table 1 shows the probability that storms of 10-, 25-, 30-, 50-, and 100-year frequency will be found in station-records ranging in length from 10 to 100 years.

Both methods of determining rainfall intensity-frequencies, discussed above, fail to yield reliable results because of inadequate data. With stations spaced so widely it is certain that storms with centers bringing intensities and amounts of rainfall in excess of anything observed will occur frequently in the area, without being recorded. For instance, the storm which produced the unprecedented flood on the Republican River in May 1935 occurred in such a way that it was not recorded at any of the Weather Bureau stations. Both methods relate to single stations and apply to limited areas, but in practice the results are actually sometimes applied to large areas. Because of the structure of rainstorms there are definite limits to the size of the area to which the data may legitimately be applied. For example, one may determine that a 24-hour storm bringing 11 inches of rain may occur at any station in the area on the average once in a century. Storm-centers of excessive intensity are small; consequently, the area over which computed intensity-frequency values would apply would not exceed a few hundred acres or a few square miles. When larger areas are involved, the average amounts to be expected would be less.

Table 1--*Probability that a storm of given frequency will appear in a rainfall-record of given length*

Length of record in years	Storm-frequency reached or exceeded once in specified number of years				
	10	25	30	50	100
10	.65	.34	.29	.18	.10
15	.79	.46	.40	.26	.14
20	.88	.56	.49	.33	.18
25	.93	.64	.57	.40	.22
30	.96	.71	.64	.45	.26
40	.99	.81	.74	.55	.33
50	.99	.87	.82	.64	.39
60	.99	.91	.87	.70	.45
70	.99	.94	.91	.76	.51
80	.99	.96	.93	.80	.55
90	.99	.98	.95	.84	.60
100	.99	.98	.97	.87	.63

Years ago Horton recognized the importance of including area in intensity-frequency indices when he said: "When a sufficient body of data is available, the envelope-curves representing the maximum average rainfall-depth to be expected over an area of any given size can be developed and an important advance in the determination of maximum rainfall-allowance will have been attained...." [4].

When sufficient data on storm-morphology becomes available to permit intensity-frequency determinations for storms rather than for individual stations, it will be possible not only to act upon Horton's suggestion, but also to determine the maximum average rainfall-depth over an area of any given size to be expected once in any given period of time.

Conclusion--In increasing the reliability of precipitation intensity-frequency determinations the number of self-recording rain-gages should be greatly increased immediately so that the accumulations of records will be delayed no longer. The installation of 400 additional recording rain-gages, as recommended by the National Resources Committee, should be considered as a mere beginning. As a matter of fact, a large number of automatic rain-gages have already been installed. One hundred are in service at the Oklahoma Climatic Research Center and 500 at the Muskingum Climatic Research Center. One hundred automatic gages are being installed in the State of Pennsylvania by the State in cooperation with the Weather Bureau and the Geological Survey. Plans are being formulated to establish approximately 100 gages in New York. The recent great expansion in the number of automatic gages in operation is due primarily to the fact that a good gage at a low price is now available for the first time.

In the end, the most fruitful line of approach to the problem of precipitation intensity-frequency will probably be through the classification of storms according to size, shape, and structure and the determination of frequencies of the various types with respect to each other. The consideration of storms rather than individual station records will yield results which are applicable to areas rather than to points.

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DISCUSSION

MERRILL BERNARD--Dr. Thornthwaite has stated that the station-year record can be taken as that of a single station under the following conditions: (1) Absolute identity in size and structure of storms; (2) uniformity in their sequence and frequency; (3) a uniformity in station-spacing; and (4) a sufficient number of stations to assure that all storm centers have been recorded.

The writer fully appreciates the contrasts in intensity, duration, areal distribution, and the configuration of pattern between selected storms, but he is also impressed with the consistent relationship between average rainfall-intensity, duration, areal distribution, and even storm-pattern evidenced in extensive studies of rainfall, such as that of the Miami Conservancy District, David E. Yarnell, Adolph F. Meyer, and Robert L. Lowry, Jr.

The spacing of Weather Bureau stations is, on the whole, not so irregular as to render the combination of their records impracticable. In any application of the station-record theory, care should be taken to select only those stations which give areal representation to the station-group. This, the writer believes, has been done in the studies previously mentioned.

As to the number of stations, the composite record is based on the theory that, within regions of like storm-visitation characteristics, one station would ultimately record every intensity-duration relationship typical of the region. If there were two stations, the entire range would be recorded in half the time, three stations in one-third the time, and so on, the division of time progressing as the number of stations increased.

The station-year method takes advantage of the similarity between the rate-area curve and the rate-duration curve, assuming the same rate of decrease in the probability of recording a particular excessive rate from the periphery of the storm to its center as in the probability of recording that rate in the comparatively few years of record for any one of the stations to be grouped.

Another conception not heretofore clearly expressed or understood is as follows: Consider, within a region of like rainfall intensity-duration characteristics, that a long (or the ultimate) record shows a particular average depth, to have visited the region on the average of once in ten years. This, for the want of a better term, let us call the "visitation"-opportunity. Suppose the area associated with this rate as shown by a typical rate-area curve is 1/100th of the area of the region, that is, there is 100 "position"-opportunities for the rate to prevail within the region. The product of these frequencies is, therefore, the probability with which any station (or unit-area) can be expected to record the particular rate.

Dr. Thornthwaite has given us a sympathetic and constructive criticism of a method of utilizing rainfall-records. The value of that method is fully appreciated by those who are called upon to bear the responsibility of design in localities far removed from individual rainfall-records of any length. For outstanding works such as those of the Miami Conservancy District [see 1 of references at end of discussion], Adolph F. Meyer [2], and the late David E. Yarnell [3], the engineering profession must be forever grateful.

There are yet several questions in my own mind regarding the station-year theory and I feel tne work Dr. Thornthwaite is doing will provide the answer to them.

Table 1--Evolution of duration-series of monthly rainfall for quadrangle 10-E

Station, years of record, station-years	Monthly depths reached or exceeded in T-years					
	5	10	15	25	50	100
Knightstown, 1869-1874, 91	8.91	10.38	10.95	11.28	13.12	16.30
Wabash, 1876-1884, 100	8.91	10.38	10.95	12.21	13.12	16.30
Lafayette, 1880-1930, 151	8.83	9.90	10.73	11.37	12.72	13.12
Mauzy, 1881-1930, 201	8.79	9.64	10.58	11.28	12.21	13.12
Worthington, 1883-1919, 238	8.98	10.13	10.69	11.28	12.21	13.94
Connorsville, 1883-1923, 279	8.91	9.95	10.69	11.37	12.21	13.12
Farmland, 1884-1930, 326	8.93	10.02	10.73	11.37	12.14	13.12
Columbus, 1884-1930, 373	8.86	9.90	10.68	11.28	12.14	12.95
Sunman, 1884-1896, 386	8.83	9.71	10.67	11.28	12.08	12.95
Delphi, 1886-1930, 431	8.45	9.54	10.50	11.07	12.08	13.12
Butlerville, 1886-1930, 476	8.77	9.65	10.58	11.37	12.21	13.12
Rockville, 1887-1930, 520	8.76	9.64	10.50	11.12	12.21	13.12
Rushville, 1888-1894, 526	8.76	9.59	10.50	11.12	12.21	13.12
Logansport, 1890-1917, 554	8.60	9.56	10.44	11.07	12.14	13.03
Marian, 1892-1930, 593	8.55	9.56	10.38	11.01	12.12	13.03
Kokomo, 1893-1930, 631	8.56	9.56	10.38	11.01	12.12	13.03
Cambridge City, 1893-1930, 669	8.60	9.58	10.31	11.01	12.12	13.01
Huntington, 1894-1920, 706	8.55	9.53	10.26	11.01	12.08	13.01
Anderson, 1895-1930, 742	8.55	9.54	10.21	11.00	12.04	13.01
Bloomington, 1896-1930, 784	8.68	9.63	10.31	11.01	12.04	13.01
Whitestown, 1897-1930, 818	8.69	9.66	10.30	11.01	12.08	13.01
Markle, 1898-1910, 831	8.64	9.65	10.30	11.01	12.04	13.01
Greensburg, 1902-1910, 844	8.64	9.65	10.30	11.01	12.08	13.01
Moores Hill, 1903-1930, 872	8.68	9.61	10.21	11.01	12.08	12.95
Greenfield, 1904-1930, 899	8.70	9.65	10.31	11.04	12.08	12.97
Shelbyville, 1905-1930, 925	8.71	9.66	10.31	11.04	12.08	12.97
Eminence, 1907-1912, 931	8.68	9.63	10.30	11.01	12.04	12.97
Monticello, 1911-1916, 937	8.68	9.61	10.30	11.04	12.08	12.97
Hickory Hill, 1913-1930, 955	8.66	9.63	10.31	11.04	12.12	12.97
Frankfort, 1914-1930, 972	8.69	9.64	10.35	11.01	12.12	12.97
Elliston, 1915-1930, 988	8.70	9.65	10.35	11.01	12.08	12.97
Green Castle, 1917-1930, 1002	8.72	9.75	10.38	11.04	12.08	12.97
Crawfordsville, 1918-1930, 1015	8.72	9.70	10.47	11.04	12.12	12.97
Royal Center, 1919-1930, 1027	8.70	9.66	10.44	11.01	12.12	12.97
Noblesville, 1920-1930, 1038	8.72	9.67	10.44	11.01	12.12	13.01
Muncie, 1921-1930, 1048	8.72	9.67	10.44	11.04	12.12	13.01
Martinsville, 1923-1930, 1056	8.72	9.67	10.47	11.04	12.12	12.97
Brookville, 1925-1930, 1062	8.70	9.66	10.44	11.04	12.12	12.97

(1) Accepting the limitations to which Dr. Thornthwaite has pointed, why should values computed by a rainfall-equation for New York City [4], as an example, developed from station-year records, compare with observed data of the single long-term record of the Central Park Station with about the same accuracy as the values computed by the equation developed from the record itself?

(2) What is the explanation for the fact demonstrated by Powell [5], Mavis [6], and the writer [7] that, for a given frequency up to once in 50 years, at least, a single equation may be used to express the relation between average intensity and duration of rainfall for periods of from one to 30 days?

(3) Accepting such a relationship, what can account for the stability of the duration-series of 30-day rainfall for quadrangle 10-E, shown in Table 1, in which it is demonstrated that after the establishment of the Weather Bureau station at La Fayette, Indiana, in 1880, the fifth to be established and at which time there had accumulated 151 station-years for the quadrangle, there has been practically no change in the series to date with 38 stations now in the quadrangle representing a composite record of 1062 station-years?

(4) We have now nearly 40 years of significant rainfall-records over eastern United States. Will periodicities established from this record, as we now define them, be changed materially when the record has reached 100 years?

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C. W. THORNTHWAITE--The stability for the duration-series of 30-day rainfall for quadrangle 10-E, referred to by Mr. Bernard and shown in his Table 1, is due to a high degree of correlation between stations. High monthly totals of precipitation are due almost invariably to large general storms which affect many stations simultaneously. In his Table, Mr. Bernard has taken the complete records for individual stations and has added them to the composite a station at a time. The fact that he found practically no change in the series as other complete station-records were added to those of the first five stations indicates that the storm-characteristics of all stations are practically identical because of the effect of general storms.

If one analyzes the data for quadrangle 10-E from the standpoint of short periods, he finds a quite different situation.

Table 1 shows the expected frequency in years for monthly rainfall of specified amounts for each period during which 200 station-years of record have accumulated. The variation in expected frequency from period to period is very great--13 inches ranging from 62 to 207 years, 12 inches from 25 to 95 years, 11 inches from 14 to 63 years, 10 inches from 6 to 24 years, 9 inches from 4 to 10 years, and 8 inches from 2 to 4 years. The expected frequencies as determined from the

Table 1--Expected frequency in years for monthly rainfall of specified amount for quadrangle 10-E

Period	Frequency once in T-years					
	13-inch	12-inch	11-inch	10-inch	9-inch	8-inch
	years	years	years	years	years	years
1856-1889 (207 station-years)	207	69	26	12	7	4
1890-1899 (202 station-years)	101	40	14	6	4	3
1900-1907 (190 station-years)	190	95	63	24	10	4
1908-1915 (201 station-years)	201	25	14	8	5	2
1916-1922 (204 station-years)	102	68	18	9	5	3
1923-1928 (187 station-years)	62	37	23	12	5	3
Composite (1252 station-years)	125	48	22	10	6	3
Indianapolis 67 years	67	33	17	11	7	3

composite record of 1252 station-years lie within the ranges established for the various periods, as would be expected, and those determined from the 67-year record at Indianapolis do also. Only one of the period-computations yields results closer to those of the composite records than do those for Indianapolis.

If one were to generalize from this single instance, he might conclude that a single record of 67 years is more reliable than 200 station-years combined from short records of a number of stations. Furthermore, he would conclude that the reliability of the station-year method is so low that the errors in determination of frequency of storm-amounts of rainfall from short records may amount to several hundred per cent. The engineer is justified in using the method in the absence of more satisfactory data but he should not be unaware of its limitations.

C. S. JARVIS--The paper and discussions as presented are intensely interesting and generally satisfactory. However, it seems advisable to consider further the representation of synthetic records involving rainfall intensity-frequency relations, as developed in Mr. Bernard's discussion.

Dr. Thornthwaite's paper has reduced to simple terms a number of observations and conclusions concerning the adequacy of records from widely scattered stations. When we realize that the odds are against any record being made of the most intense rainfalls within any given region due to the relatively small area included in the eye of the disturbance and the wide spaces between meteorological stations, we should avoid any method of analysis which tends to obscure or reduce such values as are observed. There should be some way devised for giving appropriate weight to those rare occurrences which find their way into the record, instead of submerging them with a mass of data representing medium intensities and correspondingly frequent occurrences.

By extracting a few items from Mr. Bernard's Table 1, to permit a comparison with the tabulation based upon 100 station-years it is seen that generalization regarding practical constancy would be fairly applicable to the short periodicities and not in the same degree to the longer ones.

Table 1--Evolution of duration-series of monthly rainfall for Quadrangle 10-E

Station, years of record, station-years	Monthly depths reached or exceeded in T-years					
	5	10	15	25	50	100
Wabash, 1876-1884, 100	8.91	10.38	10.95	12.21	13.12	16.30
Columbus, 1884-1930, 373	8.86	9.90	10.68	11.28	12.14	12.95
Kokomo, 1893-1930, 631	8.56	9.56	10.38	11.01	12.12	13.03
Brookville, 1925-1930, 1062	8.70	9.66	10.44	11.04	12.12	12.97

In this instance, as the number of station-years exceeds 100 years some notable high intensities disappear from the tabulation. This treatment of the data, although having notable practical advantages, has the characteristic that it may obscure values of high intensity which may be of great practical significance. If full credence is given the analysis and conclusions in Dr. Thornthwaite's paper, which so clearly portray the great odds against any record being made of a local storm and still greater odds against registering its maximum intensity at any established station, it would seem logical to apply an appropriate factor, either to reduce the expected periodicity or else to increase the intensity expected for a given frequency.

The probability that the maximum intensity of a local storm-disturbance will be observed at an official station is about equal to the chance of casting a loop over a peg, or scoring a "ringer" at the game of quoits, from random, unaimed throws. Such considerations seem to uphold the author's expressed conclusion to the effect that there is only one chance in 600 that a storm-center covering an area of 25 square miles will have its maximum intensity recorded under average conditions in the United States, where 211 automatic recording gages serve more than 3,000,000 square miles, or about 15,000 square miles per gage.

When applying observed rainfall-data to runoff-problems on a drainage-area extensive enough to accommodate two or more meteorological stations, it would seem appropriate to compute the expected frequency of intense runoff resulting from storms as correspondingly greater. Thus, severe flood-runoff resulting from 50-year rainfall-intensity as observed at either of two stations would surely account for 25-year frequency within the watershed; or taking into account the large non-record areas between stations, capable of accommodating intense local storms without impinging on the stations, the expected frequency of severe runoff might be of the order of, say, once in 10 or 15 years.

USE OF AEROLOGICAL SOUNDINGS IN DETERMINING THE SOURCES OF MOISTURE FOR PRECIPITATION

Benjamin Holzman

Meteorologists today recognize various distinct types of air-bodies that in general are characterized by a great horizontal homogeneity in physical properties. This uniformity in properties obtains through a development of a thermodynamic and hydrodynamic equilibrium at certain critical or source regions within the general atmospheric-circulation system. Eventually, after these bodies of air attain a certain potential energy of mass-distribution, polar currents begin to migrate toward the equator and tropical currents toward the pole. The character of the moisture- and temperature-modifications that occur during these migrations depends upon whether the paths of these air-bodies lie over continental or marine areas.

Polar air-masses advancing equatorward absorb moisture by evaporation, become heated, and are eventually transformed into warm, moist, tropical air-masses. Tropical air-masses, on the other hand, travelling poleward, precipitate most of their moisture, become cooled, and are ultimately transformed into cold, dry, polar air-masses. This air-mass cycle which is manifestly an expression of the general circulation of the atmosphere is closely associated with the balance of water over continental areas or, as is better known, the hydrologic cycle. In the cycle of air-mass transformation it is apparent that moist, tropical marine air-bodies must rid themselves of their high water-vapor content before they can ultimately be modified into polar air-masses, and similarly polar air-masses must gain in moisture before they can properly be transformed into tropical marine air-masses. Thus, in the alternating inundations of extensive bodies of air of different origin can be distinguished two principal classes, those that are losing their moisture and consequently contribute the major portion of precipitation on the Earth and those that are absorbing moisture and constitute the greatest robbers of moisture from continental areas.

During the past few years the United States Weather Bureau has established a network of aerological stations that daily obtain records of temperature, pressure, and humidity of the upper air. These records are made by aerometeorographs that are carried aloft to heights of approximately five km by airplanes. The stations are evenly distributed about the country, and at the present time the total number is 26. With the aid of this information it is possible to determine the sources of moisture for precipitation and to evaluate the moisture-contribution of continental evaporation to these air-masses as they invade the United States.

The amount of water (in grams), N, in the atmosphere can be calculated by the formula

$$N = (0.622/R) \int (e/T)\, dz$$

derived from the equation of state for moist air, where R = gas-constant for dry air, e = vapor-pressure of water in atmosphere, T = absolute temperature, and z = height. Theoretically, virtual temperature, T', should be used, where

$$T' = T/[1 - (3/8)\,(e/p)]$$

but it can be shown that the error involved by using T instead of T' is negligible.

By the use of aerological soundings in conjunction with synoptic weather-charts, the horizontal and vertical dimensions of air-masses may be ascertained and at the same time changes in the moisture-content for various levels may be computed. For the determination of the moisture caused by continental evaporation in the lower levels of air-masses one must be able to eliminate the increases or decreases of moisture caused by the mixing of this air with other more humid or more dry air-bodies, or similar changes of moisture-content due to actual precipitation originating from other air-masses aloft.

The trajectories of the various air-bodies may be traced with the aid of upper-air wind-data. This information, combined with a study of the aerial distribution of the equivalent depth of water in the atmosphere (total precipitable water), is useful in determining regions that may receive ample rainfall or those in which surface-evaporation will be the prevailing process.

6

These data reveal the following:

(1) That the principal sources of moisture for the United States are derived from marine air-masses whose principal water-vapor content is obtained by direct evaporation from oceanic provinces.

(2) That although approximately 75 per cent of the total precipitation over continents is returned to the atmosphere by evaporation in accordance with the hydrologic cycle, only 25 per cent is effective for reprecipitation, the remaining portion being robbed by dry air-bodies that pass off the continent with a great increase in moisture.

(3) That the absolute quantity of moisture in the atmosphere has no immediate or direct relation to the process of precipitation.

(4) That the use of aerological together with synoptic meteorological data furnishes an interesting and new approach to the problem of determination of the amount of moisture returned to the atmosphere by evaporation, interception, and transpiration. The evaporation-factor is the least understood phase of the hydrologic cycle and yet is of fundamental importance in anticipating flood and soil-erosion hazards. However, because of the complex relationships between evaporation and topography, temperature, wind, intensity and character of precipitation, types of soil and subsoil, and vegetal cover, it has been impossible to calculate accurately the quantity of moisture evaporated from watersheds by the use of empirical evaporation-formulas. The indicated procedure avoids these difficulties by measuring the actual amount of water-vapor transmitted to the air-masses involved. The calculations are, of course, limited by the number of aerological soundings available within the trajectory of the air-mass that is absorbing the ground-moisture.

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DISCUSSION

C. W. THORNTHWAITE--In his paper Mr. Holzman has pointed out an important matter which many hydrologists have overlooked. All descriptions of the hydrologic cycle and all diagrams illustrating its operation indicate that moisture evaporates from the oceans and is transported by the wind to the continents where it is precipitated and from which the course of the water is traced. Some is re-evaporated into the air, some returns to the oceans by way of rivers and underground waterflow, but nowhere is there recognition of the fact that any portion of the moisture evaporated from the land is transported by the wind back to the oceans. Mr. Holzman has indicated that the general atmospheric circulation in the United States consists of invasions alternately of great masses of Tropical and Polar Maritime air and Continental air. For interior and eastern United States the principal source of water is the rainfall that originates from great flows of Tropical Gulf and Tropical Atlantic air. He further points out that the great robbers of moisture from the land are the Polar Continental air-masses that pass off continental regions with large increases in moisture. He has found that the gain in moisture of the Polar Continental air-masses as they cross the United States, when combined with the runoff to the ocean, is roughly equal to the moisture-loss by Tropical air as it migrates across the land-areas. This is an extremely important discovery in connection with the ideas relating to local precipitation of moisture evaporated from the land. It indicates that continental evaporation as a source of local precipitation is relatively insignificant.

A further implication of Mr. Holzman's paper appears in the question of flood-control. He has indicated that the Polar Continental air-masses which flow from the Canadian prairies southward and southeastward across the Continent to the Gulf and to the Atlantic are in effect great invisible rivers transporting water from the land to the sea. An effective method of flood-control would be to prevent too great concentrations of the water from excessive and prolonged rainfall in surface-streams and rivers and instead expose as much as possible of the waters to evaporation. Proper soil and water practices, forestry measures serve this purpose and are in effect flood-control measures. It can readily be seen that any technique which would further stimulate evaporation of excessive rainfall from the land into these great atmospheric streams which in turn conduct the moisture harmlessly back to the seas also serves as an important and supplemental flood-protection measure.

O. E. MEINZER--Do the results presented in Mr. Holzman's paper make any contribution toward answering the question as to whether decreased evaporation opportunity resulting from artificial drainage has tended to decrease precipitation on the land?

B. HOLZMAN--A study of the total amount of moisture in the atmosphere during synoptic meteorologic situations and for monthly or yearly average conditions reveals that there is no immediate relation between the absolute quantity of atmospheric moisture and precipitation; or, in other words, a mere increase in the amount of moisture held in the atmosphere cannot be expected to be reflected in an increase in rainfall. In fact, it has been shown that a decrease in the amount of moisture held in the lower atmosphere is generally found to be associated with an increase in precipitation during winter over the northern Great Plains. This is caused by the greater condensation induced from upper-air invasions of Polar Pacific air by the abnormally dense, dry Polar Continental air on the surface.

It should be pointed out that, although artificial drainage will tend to reduce the amount of moisture in the lower atmosphere, land evaporated moisture furnishes only a small supply of moisture for reprecipitation over continental areas. The greatest part of the evaporation from the land is absorbed by dry continental air-masses whose moisture, in general, cannot be released immediately and invariably pass off continental areas carrying with them large increases in moisture. The principal source of supply of moisture for precipitation over continents is derived from marine air-bodies whose moisture is obtained from evaporation over oceanic areas. It is evident, therefore, that decreased evaporation resulting from artificial drainage is of no importance in influencing precipitation on land.

THE MUTUAL INTERFERENCE OF ARTESIAN WELLS ON LONG ISLAND, NEW YORK

R. M. Leggette

(Published with the approval of the Director, U. S. Geological Survey)

The withdrawal of water from a well necessarily produces a drop in water-level in the well. The ground-water level in the vicinity of the well from which the water is withdrawn likewise declines, but the amount of decline decreases with increasing distance from the well, so that a cone of depression of the water-surface in the vicinity of the well is produced. The cone of depression is an actual water-surface if the ground-water is not confined under pressure. If the ground-water is under artesian pressure, the cone of depression is a depression in the piezometric surface. If the cones of depression of two or more wells ending in the same formation overlap, interference of the wells occurs. In this case the combined yield of the wells when pumped simultaneously will be less than the sum of the individual yields if the wells are pumped separately. In choosing the proper spacing of wells from the operator's point of view, it is important to know the lateral extent of the cones of depression of supply-wells ending in a given formation. In many installations two or more wells are so closely spaced that their mutual interference is excessive.

The Lloyd sand is one of the most productive artesian aquifers on Long Island, New York. In Queens and Nassau counties during 1935 an average of about 15,000,000 gallons a day was withdrawn from about 35 wells ending in this formation, several of which yield more than 1000 gallons a minute. The Lloyd sand attains a thickness of about 265 feet in places but commonly is about 50 to 100 feet thick. It lies on a floor of more or less weathered bed-rock which beneath Long Island slopes to the southeast at about 70 to 80 feet to the mile. The formation consists, for the most part, of white sand and gravel, with some layers of clay. In places there is indication that the formation is divided into three more or less distinct water-bearing zones. In most localities the formation is commonly overlain by as much as 200 feet of tough clay. However, in places this clay is not present and there is doubtless opportunity for water to percolate slowly from the higher formations to the Lloyd sand. The formation underlies all of Long Island except its west end, where in places it has been removed by erosion. In most of its area of occurrence the water in the Lloyd sand is confined under artesian pressure. Wells drilled to the formation flow under natural head at some localities on both the north and south shores of the Island. At other localities wells that originally flowed have ceased to flow, some of them because of interference by new wells in the same formation.

In September, 1933, an automatic water-stage recorder was installed on an abandoned well ending in the Lloyd sand at the New York City Bayside pumping station. As shown in Figure 1, this well is one mile from Douglaston well No. 3 and 2.2 miles from Flushing wells No. 1 and No. 5, the nearest wells from which appreciable quantities of water are withdrawn from the Lloyd sand. Figure 2 shows that the pumpage from Douglaston No. 3 is fairly uniform as compared with the pumpage from the Flushing wells. It is apparent from Figure 2 that when pumping from the Flushing wells began in June 1934 the water-level in Bayside No. 10 began to decline rapidly. A further lowering of water-level took place in December, 1934, when the Flushing pumpage was increased. Other examples of interference between these wells both by draw-down and by recovery are shown in Figure 2.

From the Bayside record it appeared probable, as pointed out by D. G. Thompson, F. G. Wells, and H. R. Blank (Recent geologic studies on Long Island with respect to ground-water supplies, Economic Geol., June 1937), that interference, so pronounced at a distance of 2.2 miles, extended considerably farther. During 1936 more detailed studies of the head and hydraulic gradient in the Lloyd sand were begun, and instrumental records became available of water-levels at localities at considerably greater distances from the Flushing and Douglaston wells.

On January 30, 1937, the Flushing wells were shut down. On February 16, 1937, Douglaston No. 3 was also shut down. This decrease in draft rapidly produced a rise of water-level in Bayside No. 10, Whitestone No. 6, and Forest Hills No. 1. The water-level in all the wells used in the interference-tests fluctuates as much as six inches to a foot during a week in response to variations in atmospheric pressure. (The atmospheric pressure as plotted in Figure 2 up to July 14, 1936, is for 8^h a.m. and 8^h p.m. at New York City, corrected to sea-level; thereafter the graph is for the highest daily barometer at Jamaica, New York, not corrected to sea-level.) Because of the barometric effect it is not clear just when the water-level in Valley Stream No. 26 (six to seven miles from the wells at Flushing and Douglaston) began to rise as a result of this decrease in draft, but at the end of about one and one-half months there was a net rise of about 3 feet (see Fig. 2). There is even a strong suggestion that the water-level in the Freeport deep well (about 12 miles from the Flushing wells) rose as a result of this decrease in draft, for the hydrograph of this well shows an uptrend during this period as compared with a downtrend or flat trend during the same months in previous years.

The hearty cooperation of the Jamaica Water Supply Company and the New York City Department of Water Supply, Gas, and Electricity was obtained in arranging for further tests. Jamaica No. 8a and No. 17 were shut down on March 18, 1937, and it was agreed that these two wells and the New York City wells at Flushing and Douglaston would all be started up at 8^h 30^m a.m. on April 1, 1937. On this date the five wells began pumping at a combined rate of about 7,500,000 gallons a day. As a result of this increased draft the water-levels in the observation-wells mentioned above all declined, including the well at Freeport, which clearly showed a slight downward trend after April 1. The full magnitude of the decline of water-level in these wells will not be ap-

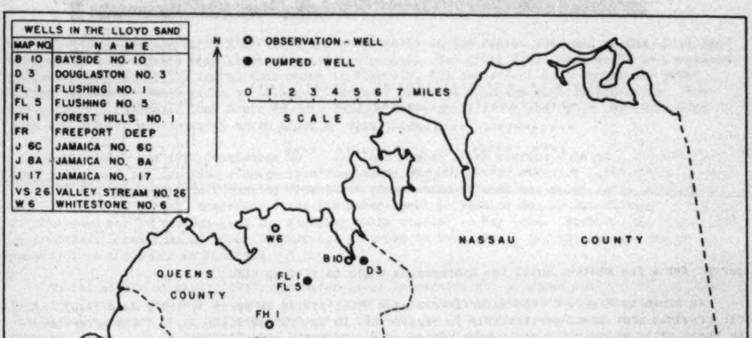
WELLS IN THE LLOYD SAND
MAP NO. NAME
B 10 BAYSIDE NO. 10
D 3 DOUGLASTON NO. 3
FL 1 FLUSHING NO. 1
FL 5 FLUSHING NO. 5
FH 1 FOREST HILLS NO. 1
FR FREEPORT DEEP
J 6C JAMAICA NO. 6C
J 8A JAMAICA NO. 8A
J 17 JAMAICA NO. 17
VS 26 VALLEY STREAM NO. 26
W 6 WHITESTONE NO. 6
N
○ OBSERVATION - WELL
● PUMPED WELL
0 1 2 3 4 5 6 7 MILES
SCALE
NASSAU COUNTY
QUEENS COUNTY
KINGS COUNTY
W6
B10
D3
FL 1
FL 5
FH 1
J8A
J17
J6C
VS 26
FR

FIGURE 1 —MAP OF WESTERN PART OF LONG ISLAND, N.Y., SHOWING WELL-LOCATIONS

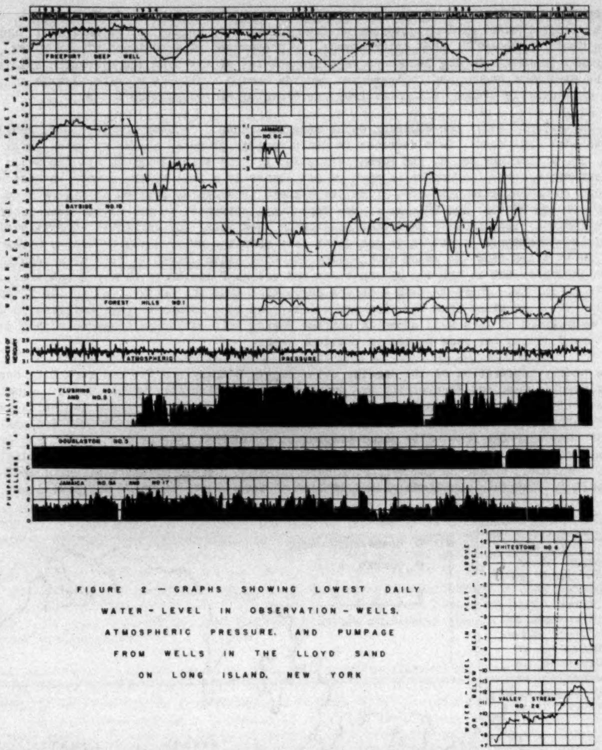

FIGURE 2 — GRAPHS SHOWING LOWEST DAILY WATER-LEVEL IN OBSERVATION-WELLS, ATMOSPHERIC PRESSURE, AND PUMPAGE FROM WELLS IN THE LLOYD SAND ON LONG ISLAND, NEW YORK

parent for a few months, until the hydrographs begin to flatten off.

As shown in Figure 2, the water-levels were still rising on April 1, 1937, as a result of the previous shut-down, particularly in Bayside No. 10 and Forest Hills No. 1. The water-levels in these wells undoubtedly would have recovered considerably more if pumping had not been started on April 1. Evidently equilibrium-conditions would not be attained for a considerable time at so great a distance from the points of withdrawal.

If there were no barometric fluctuations of water-level it should generally be possible to determine from the recorder charts the length of time required for the interference-effect to reach a given observation-well. The nature of the barometric fluctuation on April 1, 1937, was such that it was possible to determine clearly the approximate time at which the interference-effect reached two of the observation-wells. The water-level in Bayside No. 10 began to decline about two hours after the pumping started on April 1. This was presumably the result of the start of pumping from Douglaston No. 3, the nearest pumped well, one mile from Bayside No. 10. In Whitestone No. 6 there was a lag of about 28 hours, the nearest pumped wells being at Flushing, about 3.2 miles distant. These results are in fairly good agreement with the results of similar interference-tests that were carried on in Utah, in which a lag of about 13 hours was noted in an observation-well about two miles from the pumped wells (R. M. Leggette and G. H.

Taylor, The transmission of pressure in artesian aquifers, Trans. Amer. Geophys. Union, 15th Annual Meeting, 1934, p. 411, 1934).

A careful study of Figure 2 shows many examples of interference between the various wells. Table 1 indicates some of the more prominent examples.

Table 1--Summary of interference between various wells ending in the Lloyd sand on Long Island, New York, see Figure 2

Well in which water-level was affected	Pumping well that produced the effect	Month during which interference occurred	Distance between pumped well and observation-well
			miles
Bayside No. 10	Douglaston No.3	October 1936	1.0
	Douglaston No. 3	March 1937	1.0
	Flushing No. 1 and No. 5	June 1934	2.2
	Flushing No. 1 and No. 5	December 1934	2.2
	Flushing No. 1 and No. 5	March 1935	2.2
	Flushing No. 1 and No. 5	April 1936	2.2
	Flushing No. 1 and No. 5	February 1937	2.2
	Jamaica No. 8a and No. 17	January 1936	5.5
Forest Hills No. 1	Flushing No. 1 and No. 5	March 1935	2.7
	Flushing No. 1 and No. 5	April 1936	2.7
	Flushing No. 1 and No. 5	February 1937	2.7
	Jamaica No. 8a and No. 17	September 1935	1.1
	Jamaica No. 8a and No. 17	January 1936	1.1
Jamaica No. 6c	Flushing No. 1 and No. 5	March 1935	3.8
	Jamaica No. 8a and No. 17	April 1935	2.0
Valley Stream No. 26	Flushing No. 1 and No. 5	February 1937	7.1
Whitestone No. 6	Flushing No. 1 and No. 5	February 1937	3.2

It should be remembered that there are other wells in the region that end in the Lloyd sand from which considerable quantities of water are pumped. The draft from these wells is doubtless reflected in some of the hydrographs shown in Figure 2, but the effect is probably not great, either because of small yield or because of greater distance from the observation-wells. However, Table 1 indicates that there is interference between all wells ending in the Lloyd sand that are located within about seven miles of each other.

During 1932 and 1933 Douglaston No. 3 had been pumped at an average rate of 1,861,000 gallons a day, and the combined pumpage from Jamaica No. 8a and No. 17 averaged 1,606,000 gallons a day. It has been shown that pumping from these three wells affects the water-level in Bayside No. 10. It is apparent, therefore, that the water-level in Bayside No. 10 was already in a state of draw-down before pumping from the Flushing wells started in May 1934. However, by August 1935 an additional draw-down of about 14 feet had occurred in Bayside No. 10, chiefly the result of pumping from the wells at Flushing.

By the middle of March, 1937, the water-level in Bayside No. 10 stood about five feet above mean sea-level, a recovery of about 16 feet from its position in January 1937, and the water-level in Whitestone No. 6 had recovered about 12 feet, to an altitude of about 2-3/4 feet above mean sea-level. It is apparent that the water-level in both these wells had not completely recovered from the previous shut-down and that if pumping from Douglaston No. 3 had not been started on March 19, 1937, the water-levels would have risen still farther.

In 1911 several wells were drilled to the Lloyd sand at the Bayside and Whitestone pumping stations. During this year numerous water-level measurements were made in these wells. The highest water-level observed at Bayside was about eight feet above mean sea-level. At Whitestone the highest level was about 2-3/4 feet above mean sea-level. The records do not state in what month these measurements were made, and it is therefore not known whether they represent the highest or lowest water-levels during the year. So far as can be determined there was no appreciable pumpage from the Lloyd sand in 1911 from wells not operated at present and so located as to affect the water-level materially in wells at both Whitestone and Bayside. Thus, the water-level in Bayside No. 10 in March 1937 was within three feet of its highest known level in 1911. At Whitestone there was no net change of water-level during the period. As already noted, a longer period of recovery after the decreased draft in February, 1937, would have resulted in still higher water-levels in Bayside No. 10 and Whitestone No. 6. Moreover, the period from 1911 to date has been one of less than average precipitation, and it might be expected therefore that water-levels at present would be somewhat lower than in 1911 even if there had been no pumping.

The large and wide-spread draw-down that is the result of pumping from the Lloyd sand is for the most part a pressure-effect that is maintained only so long as pumping continues. When pumping is stopped the artesian pressure recovers rapidly and in a relatively short time is approaching the original pressure. The large quantity of water withdrawn from the Lloyd sand in recent years has resulted chiefly in temporary reductions of artesian pressure. If any permanent decrease in pressure has resulted, it has not been large. The interference-tests indicate that the pumping of a considerable quantity of water from the Lloyd sand at one place will measurably decrease the artesian pressure over an area of more than 150 square miles, or at distances of more than seven miles from the locality of pumping. Thus, most of the supply wells in the Lloyd sand on Long Island are causing interference in other wells. They in turn are likewise affected by interference from other supply wells.

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Jamaica, New York

DISCUSSION

C. S. JARVIS--Mr. Chairman, while accepting the data and conclusions as presented by the author as a valuable contribution to science, I must register one question regarding the apparent influence of draw-down extending to the 12-mile radius. The date of occurrence of the one example cited appears from the chart to have been some time in April, at a time when the graph is subject to a downward break, according to the experience of the three previous years as recorded on the chart. The sharp downward trend might possibly be explained on some other basis, representing interference or influence originating at locations much nearer than 12 miles. In my opinion, it would require several such coincidences, with no contrary trends, to establish the conclusion as announced by the author.

R. M. LEGGETTE--In presenting the paper, apparently either I implied conclusions not intended or Mr. Jarvis incorrectly inferred conclusions regarding interference-effects at a distance of 12 miles. The definite conclusions made in the written paper refer only to the observation-well at a distance of seven miles. The paper states that there is "a strong suggestion" that the interference reached the observation-well 12 miles from the pumped wells. This statement, I believe, is conservative because my Figure 2 shows that the water-level in the Freeport deep well rose more than one foot during February and March 1937 (following the shut-down at Flushing and Douglaston); whereas there was no rise of water-level during February and March 1934, and a decline during these two months in 1935. Furthermore, the water-level in the Freeport deep well declined during April 1937, following the start-up of pumping at Flushing, Douglaston, and Jamaica. Thus there are two cases which "suggest" that interference reached as far as 12 miles. The Freeport deep well is five miles from the nearest wells pumping from the Lloyd sand, at Garden City and at Long Beach. The well at Garden City is at an industrial plant where the draft is fairly uniform, whereas the pumping at Long Beach is seasonal. However, figures for the daily pumpage at Long Beach show no decrease in pumping rate during February and March 1937. The rise of water-level in Freeport deep well during these two months therefore appears to be the result of the decreased draft at Flushing, Douglaston, and Jamaica. The decline of water-level in the Freeport deep well in April 1937 appears to be a result of increased draft at Flushing, Douglaston, and Jamaica, for the seasonal increase in rate of pumping at Long Beach did not start until the first part of May. These conditions were not reported in the paper in part because the decline of water-level in the Freeport deep well in April had not fully developed at the time of writing and in part because since the interference was only "suggested" it did not seem necessary or desirable to lengthen the paper for the purpose of supporting a suggestion.

Although I believe that the interference does extend to a distance of 12 miles, it is my opinion that further corroborative evidence is desirable.

GROUND-WATER LEVELS IN PENNSYLVANIA IN 1936

Stanley W. Lohman

(Published with the approval of the Director, U. S. Geological Survey)

In the fall of 1931 a project was begun for obtaining systematic weekly records of ground-water levels in Pennsylvania, in cooperation between the United States Geological Survey and the

Pennsylvania Topographic and Geologic Survey. This project was described briefly at the thirteenth annual meeting of the American Geophysical Union, Section of Hydrology (Transactions 1932, pp. 373-375). This project has been in progress up to the present, and is to be continued. Some observation-wells have been discarded, and some new wells have been added. At present, weekly water-level measurements to the nearest hundredth of a foot are being made by local observers in 32 wells. One of the wells is also equipped with an automatic water-stage recorder. Most of them are shallow unused wells, and most of them are dug wells but a few are drilled.

A description of the project, together with tables showing the average weekly water-levels for all the wells and the weekly water-levels for one typical well during the four-year period ending December 31, 1935, has recently been published in United States Geological Survey Water-Supply Paper 777, "Water-levels and artesian pressure in observation-wells in the United States, 1935" (pp. 161-169). The complete records for all wells that were being observed at the close of 1936 will be published in the 1936 water-level report of the United States Geological Survey, which is now nearly ready for the press.

In Figure 1 are shown the average weekly ground-water levels for all observation-wells in Pennsylvania, and the average monthly precipitation for the State during the 5-1/3 years of record from November 28, 1931, to March 27, 1937.

The summer declines in 1933 and 1934 were arrested sharply by abnormally heavy rains in August and September of those years, and hence the lowest water-levels reached in those years were considerably higher than the minima for 1932, 1935, and 1936.

The combination of weather-conditions that produced the record-breaking floods of March, 1936, raised the water-levels in the observation-wells to the highest average stage reached during the 5-1/3 years of record. Thus, on March 21, 1936, an average stage of 17.87 feet above the selected datum-planes was reached, which is nearly 2-1/2 feet above the highest average stage previously reached--in April, 1933. The water-levels declined persistently during the spring and summer of 1936, until by September 26 the lowest average stage was reached since September, 1932. This great decline from the highest stage nearly to the lowest of record resulted from the fact that from April to September the precipitation was too light to produce any appreciable recharge except a small amount in August. The average precipitation in Pennsylvania for the year 1936, however, was slightly above normal, the excess during the first and last parts of the year exceeding the deficiency during the growing season.

The heavy precipitation at the time of the great Ohio River Flood produced the second highest average stage of the ground-water levels, namely, 16.42 feet on January 23, 1937.

Studies of rainfall and runoff covering the period of the two floods in March 1936 have been made by the United States Geological Survey, and the results for the Susquehanna Basin will be published as Water-Supply Paper 799, "The floods of March, 1936: The Hudson River to the Susquehanna River Basin."

The observation-well at Montrose, Susquehanna County, is equipped with an automatic water-stage recorder, and furnished a complete record of the water-level fluctuations at that locality during the two floods of March, 1936, and the ensuing dry period. The annual fluctuation of the water-level in this well is about the same as the average of the annual fluctuation in all the observation-wells. It is an unused well dug to a depth of 38 feet in glacial drift. A complete description of this well is given in Water-Supply Paper 777 (pp. 167-168).

The daily precipitation, the water-levels in the well at Montrose, and the discharge of Tunkhannock Creek at Dixon for the period from January 1 to September 30, 1936, are shown in Figure 2. The precipitation from March 1 to September 30 was recorded by a United States Weather Bureau rain-gage located 18 feet west of the well, but that from January 1 to February 29 was recorded by a Weather Bureau gage at Towanda.

The Montrose well is on a sloping upland in the headwaters of Wyalusing Creek, but, as this stream is not gaged, Tunkhannock Creek was selected as it is the nearest small stream for which discharge-measurements are available, the geologic and topographic conditions in the two basins being similar. The well is near the headwaters of Tunkhannock Creek and only about 20 miles north of the gaging-station at Dixon. The stream-discharge was measured by the United States Geological Survey in cooperation with the Pennsylvania Department of Forests and Waters.

The first part of January, 1936, was relatively mild and had several rains which produced some runoff and slight rises in the water-table, as shown in Figure 2. During the latter part

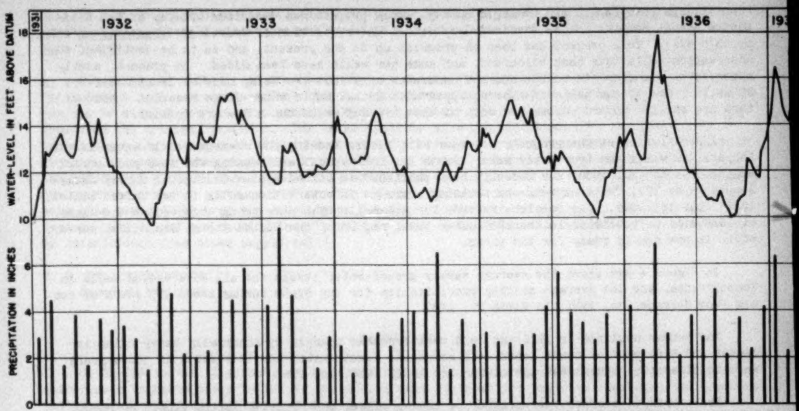

FIG. 1—AVERAGE WEEKLY GROUND-WATER LEVELS IN PENNSYLVANIA AS RECORDED BY ABOUT 32 OBSERVATION-WELLS, AND AVERAGE MONTHLY PRECIPITATION FOR THE STATE, DECEMBER 1, 1931 TO MARCH 31, 1937

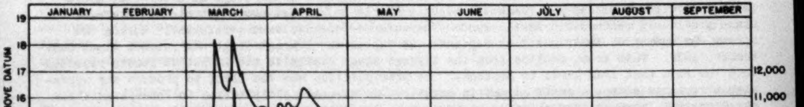

FIG. 2—GRAPHS OF WATER-LEVEL IN OBSERVATION-WELL AT MONTROSE, PA., OF DISCHARGE OF TUNKHANNOCK CREEK AT DIXON, PA., AND OF DAILY PRECIPITATION AT TOWANDA OR MONTROSE, PA., JANUARY 1 TO SEPTEMBER 30, 1936—PRECIPITATION NOT RECORDED AT MONTROSE IN JANUARY AND FEBRUARY

of January and most of February, the weather was characterized by unusually heavy snowfall and unusually low temperatures. There was little or no ground-water recharge during this period, as is shown by the steady decline of the water-table.

A general thaw began about February 25 and continued to the beginning of the flood-period. There was an accompanying rise in the flow of Tunkhannock Creek, which culminated in a peak on

March 1. The melting of part of the snow and frost apparently released considerable water downward to the water-table, for the water-level in the well rose nearly two feet by March 1. The water-level continued to rise until on March 10, just preceding the first flood, it stood nearly 3-1/2 feet higher than on February 25, and only four feet below the land-surface. The effect of the two storms which produced the two flood-peaks is clearly shown by the hydrographs. The water-level rose about three feet during the first rain. A slightly higher point was reached during the second storm, which was of much greater intensity. At the highest point the water-level stood less than one foot below the land-surface.

The abnormally high water-levels reached in this well, as in other shallow water-table wells throughout much of the State, appears to be due to the following well-timed combination of events: The general thaw apparently caused wide-spread recharge which continued up to the time of the flood, so that just prior to the flood the ground-water levels were still rising rapidly. The rapid rise of the ground-water levels indicates that there probably was considerable water in transit within the zone of aeration, though not enough to produce complete saturation. The additional water derived from the storms which produced the floods appears to have been sufficient to complete the saturation of a considerable part of the zone of aeration, which greatly accelerated the rise of the water-table. Thus, a large part of the recharge at the time of the floods appears to have come from the water that was already in the zone of aeration, and which was derived from snow that fell some time before the floods.

The question has been asked as to why the ground-water levels and also the stream-flow declined to such a low stage by the end of September, whereas exceptionally high ground-water levels were recorded during March and the first half of April. As stated above, the answer to this question appears to be that there was insufficient precipitation to produce ground-water recharge between the middle of April and the end of September, except for a slight amount of recharge in June and August. The accumulated deficiency in precipitation for Pennsylvania from April 1 to September 30 was 4.37 inches, including an excess of 0.73 inch for August. In material of rather low specific yield, such as comprises the larger part of Pennsylvania, the water-table may decline rapidly unless there is a frequent recharge. After a prolonged dry spell any rain which falls must first satisfy the deficiency in soil-moisture before recharge can take place. For example, only 0.51 inch of rain fell at Montrose during July 1936, which was 3.59 inches below normal. The 1.55 inches of rain that fell on August 6, following this dry period, had practically no effect on either the water-table or the flow of Tunkhannock Creek, indicating that the water was largely used to replenish the soil-moisture. A total of 6.00 inches of rain fell at Montrose during August, which was 1.93 inches above normal, yet the water-table did not respond until nearly the end of the month, and by September 5 had risen only about 0.10 foot.

Thus, despite the high stage in March and April, 1936, the water-table had declined by May 15 to an average stage that was lower than that on any previous May 15 during the period of record except in 1934. Hence, the very low ground-water levels and stream-flow in the fall were in part the result of conditions that existed prior to May 15 and were in a measure forecast by the water-levels on that date.

A brief study was made of the relation between the weekly runoff of the Susquehanna River Basin above Marietta from May 1 to September 30, 1936, and the quantity of ground-water discharge represented by the average weekly decline of the water-table, as shown by ten representative observation-wells in that basin.

It was found that to provide a sufficient quantity of water from underground storage to account for the stream-flow, exclusive of the storm-runoff, and for the probably ground-water evaporation and transpiration, a specific yield of the unwatered materials of approximately five per cent must be assumed. On detailed investigation, the actual specific yield may prove to vary considerably from this figure, but the computation is significant in showing that there is a reasonable quantitative relation between the underground storage as represented by the water-levels in wells and the flow of the streams.

U. S. Geological Survey,
Washington, D. C.

DISCUSSION

O. E. MEINZER--The data on ground-water levels seem to show rather definitely: (1) That there was unusually large ground-water recharge in the spring of 1936, much of which occurred between February 25 (when the frost in the ground ceased to be an effective barrier) and the advent of the flood; (2) that the low stream-flow in the fall was due chiefly to the exceptionally meager recharge during the latter part of spring and in the summer and fall; and (3) that the quantity of stream-flow tallies approximately with the decrease in ground-water storage in view of the low specific yield of the water-bearing material in the unwatered zone and the heavy demands made by the vegetation on water from the zone of saturation in dry seasons.

WATER PUMPED FROM THE MINES OF THE ANTHRACITE-REGION OF NORTHEASTERN PENNSYLVANIA

Dever C. Ashmead

One of the most important physical factors that influence the cost of mining anthracite is water. Water is a necessity in cleaning the product in the breakers but its presence below ground is a detriment. Water must be kept from those parts of the mine where the men are working. Large amounts of water may flood the mine. Smaller amounts cause trouble by wetting the coal, which makes each shovelful heavier and harder to handle. The drill-holes may become wet, and complications in blasting result. Water dripping from the roof wets the clothes of the workmen and reduces their efficiency. It accelerates decay of mine timbers and ties unless they are entirely submerged, and therefore increases the expense of maintenance. The greater the quantity of water, and the higher the lift, the greater is the cost of pumping, and as the mining proceeds, the cost tends to increase. For all these reasons, the water-problem requires special attention in any study of the trends of labor productivity in anthracite mining. The data in this paper have been obtained in the course of a study of "Mineral technology and output per man," made as a part of the Works Progress Administration's National Research Project on Reemployment Opportunities and Recent Changes in Industrial Techniques (Factors influencing the cost of mining and output per man in the Anthracite Region of Pennsylvania, by Dever C. Ashmead, in preparation).

To give some idea of the great importance of the effect of water on the cost of anthracite, let us examine some figures. In 1935, the weighted average maximum depth of workings for the Anthracite-Region of northeastern Pennsylvania was 549 feet. The Department of Mines of the Commonwealth has estimated that the cost of pumping 1,000,000 gallons of water to an elevation of ten feet is 40 cents. In 1935, there were pumped from the mines 360,694,000,000 gallons of water. For every ton of coal produced from underground workings in 1935, more than 33 tons of water were pumped.

Where does this water come from? The most important source is the rainfall within the area itself. Measurements of rainfall, taken from the reports of the United States Weather Bureau for the various stations in the Anthracite-Region, are shown in Table 1. It will be seen from Table 1 that, in 1935, the greatest rainfall occurred in what is known as the Eastern Middle Field, where it amounted to 45.58 inches, and the least occurred in the Wilkes-Barre and Nanticoke areas, with 40.47 inches. The average for the whole Anthracite-Region was 43.6 inches.

Table 1--Rainfall and drainage-area in the Anthracite-Region of Pennsylvania[a]

Year	Northern Field			Eastern Middle Field No. 4	Western Middle Field No.5	Panther Creek No. 6	Other Southern Field No. 7	Anthracite-Region No. 8
	Lackawanna No. 1	Wilkes-Barre No. 2	Nanticoke No. 3					
	(b)	(c)	(c)	(d)	(e)	(f)	(g)	
				Rainfall in inches				
1935	44.21	40.47	40.47	45.58	43.26	42.48	45.21	.....
1931	30.54	32.38	32.38	38.13	31.98	35.38	32.99	.....
1927	45.33	46.70	46.70	58.97	56.20	56.66	48.61	.....
1920	42.77	39.11	39.11	65.09	42.95	35.24	49.58	.....
1917	33.00	30.31	30.31	47.36	52.04	46.32	43.99	.....
1912	42.56	35.15	35.15	53.57	57.55	46.21	50.85	.....
1907	34.53	39.38	39.38	43.55	52.18	42.19	48.81	.....
1902	45.05	43.78	43.78	54.42[h]	61.85	65.05[i]	61.16	.....
				Drainage-area in square miles				
	151.40	73.1	51.6	100.5	122.4	18.1	117.2	634.3

[a] Source of data is United States Weather Bureau. [b] Scranton. [c] Wilkes-Barre. [d] Freeland. [e] Girardville. [f] Lansford. [g] Pottsville. [h] Average Wilkes-Barre and Mauch Chunk. [i] Mauch Chunk.

The drainage-areas were determined from the topographic maps of the United States Geological Survey. They embrace all areas underlain directly by the anthracite-bearing formations, including the Pottsville basal conglomerate and the Mauch Chunk red shale. To these have been added certain areas outside the coal-measures where the surface-runoff would traverse outcrops of the anthracite-beds before running into the permanent streams. So defined, the total drainage-area was calculated to be 634.3 square miles, which is about 210 square miles more than the area underlain by workable beds of anthracite. It was a simple matter to determine the drainage-area of the Panther Creek District, the Southern Field, the Western Middle Field, the Eastern Middle Field, and the Nanticoke District, where the outcrops of the coal-measures coincide with the boundaries of the watersheds. There is some question as to the exact drainage-area of the Lackawanna and Wilkes-Barre districts, as there are a number of small streams which rise outside these districts and flow across them. If these streams were taken into consideration, the calculated drainage-area would be slightly larger. Within the accepted drainage-area the total precipitation in the Anthracite-Region in 1935 was about 481,101,000,000 gallons of water. The amount of rainfall in the separate divisions is shown in Table 1.

Besides the water that comes from rainfall within the Anthracite-Region, other sources of water must be considered. These include:

(1) The Susquehanna River, which flows through the entire length of the Wilkes-Barre District and crosses part of the Nanticoke District. There is known to be considerable leakage from this River into the collieries. One colliery was drowned out by a break-through to the bottom of the River many years ago, and has never been pumped out. In another colliery, the water in the shaft rose and fell with the changes in the level of the River, but the leak stopped itself by silting and this mine has since been dewatered. In times of flood, extensive break-throughs may occur, and even if they can be stopped, the mines have to be dewatered. In March 1936, one of the tributaries of the Susquehanna overflowed and broke through into one colliery, from which, in turn, the water flooded five other collieries. As a result, about six large collieries are still idle, although dewatering has been in process for almost a year.

(2) Where the streams cross the outcrops of the coal-measures, a considerable quantity of water enters the rocks.

(3) Ground-water influences the amount of water pumped.

(4) A special case of ground-water is the "Buried Valley" of the Wilkes-Barre and Nanticoke districts. This is thought to be the original channel of some preglacial river, or perhaps a series of lakes which, during the glacial period, were filled with sand and gravel, creating thick beds of quicksand. These are kept saturated with water by the Susquehanna River which flows across the Valley. As this Buried Valley is underlain by rich beds of coal, leakage into the mines occurs in volume.

The infiltration of water is aided by the folding of the coal-measures characteristic of some parts of the Anthracite-Region. It is therefore well to review briefly the geologic structure of the several producing fields. The Panther Creek District and the Southern Field are really one and extend from Mauch Chunk almost to the Susquehanna River in the vicinity of Dauphin. In this area the beds are steeply pitching and reach an estimated maximum depth of about 4500 feet. The Field is long, narrow, and deep--somewhat in the shape of an enormous canoe, with one end split into two parts. The coal-beds are underlain with the Pottsville conglomerate--a massive, tightly cemented, large-grained conglomerate, relatively impervious except where broken--and below this lies the much-fractured Mauch Chunk red shale. The coal-beds and associated rocks stand on edge along the outcrops and afford a ready entrance to water. In some places, through folding and faulting, the Pottsville conglomerate has been cracked and broken, and the waters in the shales are free to move upward through the cracks in the conglomerate and to reach the coal-beds. Just how much water enters from this source is unknown, for in some of the deep mines of the Anthracite-Region the deepest parts are the driest. The average weighted maximum depth of the mine-workings in the Panther Creek District is 821 feet, and in the main Southern Field, 660 feet.

The Western Middle Field is also canoe-shaped but very much broader in the beam than the Southern Field. Otherwise the conditions are the same, except that the northern outcrop along a portion of the Field does not have the steep pitches of the southern outcrop. The weighted average maximum depth of workings in this Field is 615 feet.

The Eastern Middle Field has the same canoe-shaped structure with steep sides. Instead of one basin, however, it consists of a series of basins, and they are not deep compared to the other fields. The weighted average maximum depth of workings is 332 feet.

The Lackawanna, Wilkes-Barre, and Nanticoke districts make up the Northern Field, which is one large basin, shallow in the northern part and slightly pitching at the outcrops, and flattening toward the center. As the basin extends southwest, the depth of the measures increases, and the pitch of the outcrops increases until in the Nanticoke District it locally approaches the vertical. The coal-beds of the Northern Field reach their maximum depth in the Nanticoke District at 2500 feet. The calculated weighted average depth of the mine-workings is 361 feet for the Lackawanna District, 477 feet for Wilkes-Barre, and 772 feet for Nanticoke.

The influx of water into the mines is further aided by the operations of mining itself. The principal examples of this factor may be classified as follows: (1) The driving of rooms or chambers to the outcrops and the resulting crop-falls make openings direct from the surface into the underground workings. (2) The robbing of pillars causes the roof to fall, and these falls may travel to the surface and open channels for surface- and ground-water to enter the mines. (3) Strip- or open-cut mining has greatly accelerated the infiltration of water. Stripping the overburden along the outcrops often leaves natural catch-basins in which surface-water collects. The water may slowly seep through into the mine-workings, or sometimes the stripping operation cuts across the ends of old mine-chambers, opening direct channels underground. Many collieries adjacent to strippings have experienced an increase in the volume of water to be handled, and report that the time-interval between the fall of rain and the appearance of water underground has been greatly reduced. Under these conditions it is not uncommon for a heavy rain to drown out the workings for a few days.

In addition to the initial volume of water resulting from rainfall and ground-water, there is a secondary burden of pumping that results from recirculation. Water is pumped to the surface and flows on the surface for a short distance, and then part of it may reenter the same mine or an adjoining mine through surface-cracks; or after the mine-water reaches the surface-streams, there is a chance for further leakage underground before it finally passes from the region.

In parts of the region a considerable amount of silt or back-filling is used for roof support. This means crushing the waste mine-rock to a small size and flushing the crushed material into the mine with water. The volume of water used is from eight to ten times that of the flushing material. This water must be repumped to the surface. It would probably not be out of the way to say that at least two billion gallons yearly, resulting from back-filling, have to be handled in this manner in addition to the huge volume of recirculation resulting from other causes.

Table 2--Volume of water pumped from the mines, in relation to total rainfall and output of coal, in the Anthracite-Region of Pennsylvania, 1935[a]

District	Total rainfall (million gallons)	Tons of coal produced, net tons[b]	Water pumped from mines (million gallons)			Water pumped in per cent of rainfall[e]	Tons of water pumped per ton of coal produced[b, e]
			From operating mines[c]	From idle mines[d]	Total		
Lackawanna - District No. 1	116,323	10,391,237	72,398	17,113	89,511	76.9	35.88
Wilkes-Barre - District No. 2	51,413	8,695,673	58,386	24,591	82,977	161.4	39.74
Nanticoke - District No. 3	36,291	8,184,742	24,451	6,516	30,967	85.3	15.76
Eastern Middle - District No. 4	79,608	4,100,257	18,620	13,040	31,660	39.8	32.16
Western Middle - District No. 5	92,021	8,703,057	32,041	34,427	66,468	72.2	31.81
Panther Creek - District No. 6	13,362	1,765,047	22,837	......	22,837	170.9	54.08
Southern Field - District No. 7	92,083	3,236,575	13,150	23,124	36,274	39.4	46.68
Total Anthracite-Region No. 8	481,101	45,076,588	241,883	118,811	360,694	75.0	33.33

[a] Source of data is Department of Mines, Commonwealth of Pennsylvania. [b] Does not include strip-mined, washery, and dredge coal. [c] Computed from the 1935 returns, which definitely relate to gallons of water actually raised to the surface in that year. [d] Pumping data were not reported for mines idle throughout 1935; in order to complete the record, each colliery known to be idle in 1935, but not flooded or abandoned, has been included at the gallonage reported in the last year of record (1931, or prior year of last production); as the returns for 1931 and earlier years, in some instances, represented pump-capacity rather than gallonage lifted, the figures for the idle mines may be considerably in excess of the volume actually pumped in 1935. [e] Includes water pumped from idle mines.

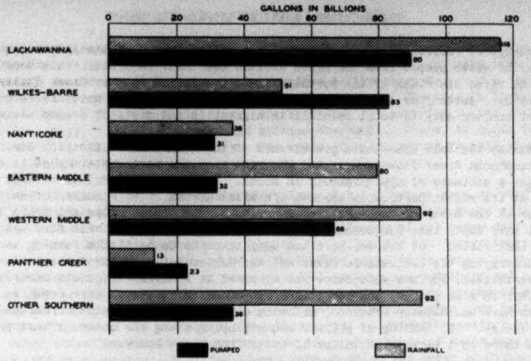

FIG. 1—TOTAL RAINFALL AND WATER PUMPED FROM MINES IN THE ANTHRACITE-REGION IN 1935

[WATER PUMPED INCLUDES COLLIERIES IDLE BUT NOT ABANDONED]

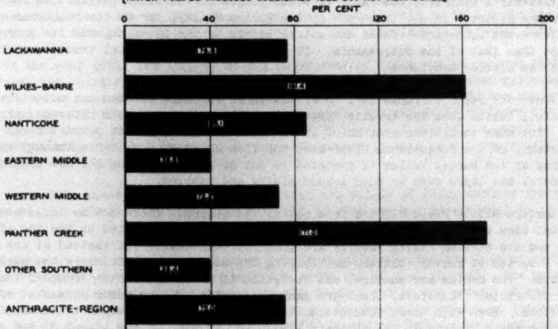

FIG. 2—WATER PUMPED FROM MINES IN PER CENT OF TOTAL RAINFALL IN AREA, 1935

[DATA FOR WATER PUMPED INCLUDE COLLIERIES IDLE BUT NOT ABANDONED]

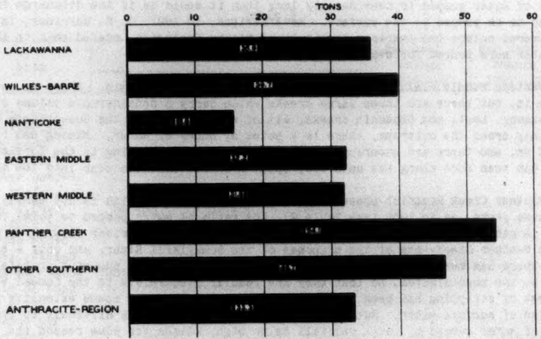

FIG. 3—TONS OF WATER PUMPED PER TON OF COAL PRODUCED, 1935

As a result of recirculation, it happens that in some parts of the Anthracite-Region the total volume of water pumped from the mines exceeds the total rainfall. This condition is most marked in the three districts of the Northern Field and in the Panther Creek Valley (see Table 2 and Figure 2). Aside from the last-named District, the record for which is hard to interpret, the ratio of pumping duty to total rainfall is highest in the district around Wilkes-Barre.

The reasons for this unenviable preeminence of the Wilkes-Barre District are as follows: (1) The Susquehanna River flows across the District from the northeastern edge to the southwestern edge--a distance of approximately 12 miles. (2) The Buried Valley extends the same distance, and at its widest portion is about 1-1/2 miles across. (3) A number of small streams rise outside of the District, and their waters flow across the outcrops and traverse the District until they empty into Susquehanna River. (4) Large areas have been first-mined, second-mined, and then robbed. Of course, care has been taken to do as little robbing as possible in the areas underlying the Susquehanna River and the Buried Valley so that they will not be disturbed; nevertheless, surface-subsidence has occurred at a number of points underlain by the Buried Valley; in some places, the subsidence has amounted to two or more feet; as a result, small cracks have undoubtedly occurred, allowing water to enter the mines from the quicksands of the Buried Valley. (5) Robbing of pillars and stripping along the outcrops have progressed to a point where there is a very great influx of water from these sources.

In the Lackawanna District, although robbing has been carried on to a greater extent than in the Wilkes-Barre District, the ratio of water pumped to the total rainfall is not so great. The Lackawanna District is not traversed by the Buried Valley, nor by the Susquehanna River. Another river--the Lackawanna--flows the entire length of the District, but its size is considerably less than that of the Susquehanna. It has at times caused local trouble, particularly in March 1936, as already mentioned.

The Nanticoke District ranks next to Wilkes-Barre in ratio between the water pumped and the total rainfall (aside from the erratic Panther Creek District, to which reference will shortly be made). The same conditions that exist in the Wilkes-Barre District prevail here, but to a smaller extent, as the Susquehanna River does not flow as great a distance through the District, and the area of the Buried Valley it contains is not so great. Mining has not progressed so far, nor in general has there been as much second-mining and robbing.

The Eastern Middle Field differs from all of the others. There are no large rivers or streams that flow across the coal-measures. The coal itself is located on the top of a broad mountain, and the streams rising locally are comparatively small; but instead of one coal-basin, there are a series of basins, thereby multiplying the number of points where the streams traverse the outcrops. The basins are shallow, and depletion is probably further advanced than in any of the other districts. Therefore, there are many crop-falls, giving ready access of surface-water into the mines. Even with these conditions, the ratio of water pumped to total rainfall is much less than for the districts in the Northern Field, and is next to the lowest of any district in the whole Anthracite-Region. As this Field is located on the top of the mountain, two drainage-tunnels have been driven, which dewater a considerable portion of two of the basins. As a result, the amount of water pumped is considerably less than it would be if the discharge from these tunnels had to be pumped to the surface. Nevertheless, in 1921, J. B. Warriner, in discussing a paper delivered before the American Institute of Mining Engineers, stated that in this field 16 tons of water were pumped for every ton of coal produced.

The Western Middle Field is really one great, canoe-shaped basin. There is no large river traversing it, but there are three large creeks which carry a considerable volume of water. They are the Mahanoy, Lost, and Shamokin creeks, all of which flow into the Susquehanna River. Wherever they cross the outcrops, there is a point of entry of water. Mining has been extensively carried on, and there are numerous crop-falls and breaks extending to the surface. Much stripping has been done along the outcrops, opening direct channels down into the mines.

The Panther Creek District presents a contradictory record which is not easily accounted for. In some years, as in 1935 (see Table 2), the ratio of water pumped to total rainfall is high, and in other years it is relatively low. There is no large river flowing through the area other than Panther Creek--one of the branches of the Schuylkill River, and only a small branch at that. There has been a great deal of robbing, which has caused numerous crop-falls. The falls stand out on the mountainside, so that they are readily discernible to the casual visitor. A large amount of stripping has been undertaken and, of course, this opens extensive areas to the infiltration of surface-water. But, even with these factors, it is difficult to understand how the ratio of water pumped to total rainfall is so high, unless for some reason the volume derived from ground-water is higher in this District than in other districts, or else there were errors in the figures reported to the State Department of Mines.

The Southern Field has the lowest ratio of water pumped to total rainfall of any of the anthracite-districts. Although mining began in this District at about the same time as in the others, the tonnage produced to date is small in relation to the resources. As a result, there have been fewer surface-breaks than in any of the other districts. The area is large and the extent of mining is small. The Schuylkill River, which crosses the District in the vicinity of Pottsville, is not large. The other creeks and streams are small. Hence, as might be expected, the ratio of pumping to total rainfall is low. The ratio of water pumped to coal produced, on the other hand, is high.

The data used in this paper to calculate the volume of water pumped were secured from the records of the Pennsylvania Department of Mines. For many years, mine-operators have been required to make an annual return regarding the number and gallonage of the pumps delivering water to the surface. Since 1932, the Department's inquiry has called for the "approximate number of gallons delivered to the surface per day of 24 hours." Pump-capacity is generally much in excess of the average volume pumped, but study of the individual reports has convinced the writer that the returns for 1935 may be accepted as representing not capacity but the volume of water actually lifted. Many of the larger companies maintain systematic records, based upon daily or hourly weir-measurements, from which the average daily gallonage may be determined with a high degree of accuracy. Other companies are in a position to estimate the volume of water handled from the pump-capacities, and from observation of the flumes through which the water is discharged. For these reasons it is concluded that the computations in Table 2 give a reasonably close approximation of the total volume of water raised in 1935. (The computations include, however, allowances for the collieries idle in 1935, based upon what they reported in 1931 or in the last prior year of operation. As explained, the returns prior to 1932 sometimes represented pump-capacity.)

Prior to the year 1932, the inquiry of the Department of Mines was so phrased that in a good many cases the operator seems to have reported pump-capacity, rather than gallonage actually raised. For this reason the published totals of water pumped before 1932 are subject to an unknown, though substantial, discount. However, the writer has carefully reviewed the annual records of each colliery, and has selected a group of 73 identical operations which he is satisfied have consistently reported the quantity actually pumped in each year. The record for these 73 collieries is summarized in Table 3.

It is clear from these identical operations that the volume of water handled increased sharply between 1927 and 1935, although the rainfall in 1935 was not exceptional, as is shown by Table 1.

The evidence at hand indicates that under present conditions over the Anthracite-Region as a whole, about 33 tons of water must be pumped for every ton of coal hoisted. The ratio is affected by current fluctuations in the demand for the product and in the amount of rainfall. When allowance is made for these variables, a definite trend is observable toward an increase in water handled per ton of coal. (The results for 1935 differ in some respects from those obtained by the writer in an earlier study--Anthracite-losses and reserves in Pennsylvania, Topogr. Geol. Sur. Pennsylvania, Bull. M-8, 1926. The earlier study was in gross tons rather than net tons;

Table 3

Item	Year			Per cent of change	Per cent of change
	1927	1931	1935	1927-1931	1931-1935
Number of collieries included	73	73	73	0	0
Gallons of water pumped to surface per minute	264453	273134	321847	+3.3	+17.8
Net tons of fresh-mined coal, excluding stripping	29542163	27371044	23995130	-7.3	-12.3
Ratio of tons of water pumped per ton coal	19.53	21.77	29.26	+11.5	+34.4

strip-mined, washery, and dredge coal were included in computing ratios of water pumped to coal produced; and the primary data were sample returns only, secured from about 37.7 per cent of the then operating collieries. All ratios of tonnage of water pumped per ton of coal are, of course, much affected by the state of trade.)

This trend toward a greater volume of water per ton of coal seems likely to continue. Extension of the area mined, and especially the area of pillar-robbing and of stripping, multiplies the number of openings admitting water to the mines. The increase in depth of workings tends to draw ground-water from untapped reservoirs at greater distances. Early artesian wells in the Lackawanna District have now gone dry, apparently because the water that they formerly yielded has been diverted into the mines. As the area of virgin coal is exhausted, pillar-robbing operations will more and more approach the streams and the Buried Valley. Meanwhile, the growing depth of the workings increases the average height to which the water handled must be raised. The conclusion seems clear that more pumping must be anticipated in the Anthracite-Region of northeastern Pennsylvania.

[Note--The data in this paper are preliminary results of a study of "Mineral technology and output per man" made as part of the Works Progress Administration's National Research Project on Reemployment Opportunities and Recent Changes in Industrial Techniques, in cooperation with the United States Bureau of Mines. They are published with permission of the Director of the National Research Project and the Director of the Bureau of Mines.]

U. S. Bureau of Mines,
Washington, D. C.

DISCUSSION

C. S. JARVIS--During the presentation of this paper, my "rough-and-ready" calculations disclosed the fact that the volume pumped annually from the Anthracite-Region represented practically the total precipitation falling upon the Anthracite-Region area, something over 600 square miles. It was not surprising, therefore, to find that different districts within the Anthracite-Region pumped annually less than 40 per cent, while others pumped more than 140 per cent, of the annual precipitation falling on the respective areas. The explanations of the author reasonably account for such variations through differences of soil-permeability, or as the result of subsidences, strip-mining, and other disturbances of the surface- or subsurface-structure.

The fact that from seven to 20 or more tons of water are pumped for every ton of coal produced, and that both the pumping head and the volume are increasing yearly, should be quite impressive to those who must pay the rising unit prices of anthracite.

In my opinion, the outflow from drainage-tunnels should be added to the volume of water pumped from mines in order to give a comprehensive picture of the problem. Apparently, in one instance the deficiency of pumpage was partly explainable through the effect of a drainage-tunnel piercing the mountain at an intermediate level.

SOLUBILITY OF LIMESTONE

C. S. Adams and A. C. Swinnerton

The unique characteristics of the physiography and hydrology of limestone-areas are causally related to the solubility of the rocks. The evolution of topography, of rock-permeability, of ground-water circulation in limestones depends upon the solutional work in the limestone. Hence the nature of the solubility of limestone is an essential consideration in the understanding of the physiography and hydrology of karst terranes.

A number of problems arise when limestone-solubility is studied. However, the one which this paper considers is related to the apparent supersaturation of ground-water with $CaCO_3$.

The qualitative relationship of CO_2 in promoting limestone-solubility has long been known. Likewise the effect of vegetable acids, such as humic acid, resulting from the presence and decay of organic constituents in the soil has been recognized. Murray and Love [see 1 of references at end of paper], for example, experimented with the liquids from organic soil materials and found notable leaching of limestone-fragments. Terzaghi [2] has pointed out the appearance of greater solubility on surfaces overlain by vegetation than on bare rock-surfaces.

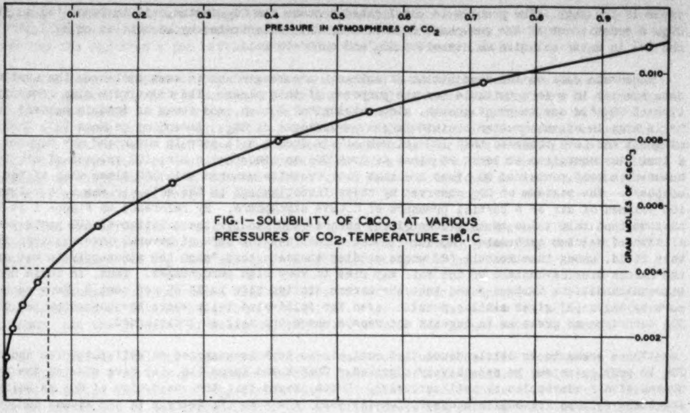

FIG. 1—SOLUBILITY OF $CaCO_3$ AT VARIOUS PRESSURES OF CO_2, TEMPERATURE = 16.1°C

However, none of the processes has been studied in the detail necessary to indicate the actual steps involved. The present paper offers a theoretical explanation of one of the several phases of the problem--that which deals with the supersaturation of ground-water solutions. Its relative significance must await experimental check and the evaluation of other processes which undoubtedly effect solution of limestone. The present discussion concerns itself with: (1) The solutional effectiveness of CO_2 dissolved in water; (2) a possible source providing for the enrichment of the CO_2-content of ground-water in the soil where bacteria, vegetation, and decaying organic matter are present; (3) the physico-chemical principles of dissolved gases which permit the retention of CO_2 in a supersaturated water-solution so that it may accomplish bed-rock corrosion.

Solubility of $CaCO_3$ in CO_2-solutions--The most complete summary and theoretical analysis of the solubility of calcium carbonate in water is found in the papers of J. Johnston [3]. He presents the complete solubility-curve of calcium carbonate which shows the concentration of calcium in solutions at equilibrium in the system CaO-H_2O-CO_2. This graph is made up of three curves, along which the stable solid phase is hydroxide, carbonate, and bicarbonate, respectively. The first extends up to partial pressures of CO_2 equal to 10^{-14} atmospheres at 16° C; the second, starting from this transition-point, decreases to a minimum and then rises again, as the values of the partial pressure of CO_2 increase continuously, until the partial pressure reaches 15 atmospheres; beyond this second transition-point the bicarbonate is the stable phase.

Since Johnston plotted his graph as the logarithm of the concentration of the calcium ion versus the logarithm of the partial pressure of CO_2, and since a very small section of his curve applies to this problem, only the relationship of calcium carbonate dissolved to partial pressure of CO_2 is presented here in Figure 1.

Under ordinary conditions when air exerts a pressure of one atmosphere the partial pressure of CO_2 is 0.0003 atmosphere. At this pressure about 63 parts per million of calcium carbonate (Fig. 1)--equivalent to 0.00063 gram moles of calcium carbonate per liter--can be dissolved. From the shape of the graph it is indicated that at low pressures a small increase in the partial pressure of CO_2 corresponds to a relatively large increase in the solubility of calcium carbonate.

Ordinarily ground-water concentrations of calcium carbonate do not exceed 400 parts per million; in fact, most ground-waters show under 200 parts per million [4]. Extrapolating the curve of Figure 1 to find the partial pressure of CO_2 corresponding to 400 parts per million of calcium carbonate gives a value of about 0.065 atmosphere. The problem, therefore, is to account for the increase in concentration of CO_2-equivalent to the change of 0.0003 atmosphere to 0.065 atmosphere.

Carbon dioxide-content of the soil--It is apparent that other sources of CO_2 higher in concentration than that found in the atmosphere must be sought. The source to be considered in this paper is the soil. The problem is complicated because the CO_2 in the soil is found (1) as free CO_2, a constituent of the gas-phase of soil-air, (2) concentrated by adsorption on soil-particles, and (3) in water-solution as dissolved CO_2 and carbonic acid.

Accurate data on the composition of soil-air are meager and in most instances the available data are not in a form suitable for the purposes of this paper. The relatively high concentration of CO_2 "is due to plant growth, micro-biological action, and decay of organic matter" [5]. Soils high in organic matter contain larger percentages of CO_2. According to Roth [6], Boussingault and Levy observed that 100 volumes of air from a soil poor in humus and not manured for a long time contained at least 25 times as much CO_2 as atmospheric air; 100 volumes of air from humus-rich soil contained 90 times and that from recently manured soil 250 times that of the atmosphere. The maximum of CO_2 observed by these investigators in the soil-air was 9.74 volumes in 100 volumes of air or a partial pressure of 0.0974 atmosphere. By reference to Figure 1 it is obvious that this value is in excess of the amount required for the solution of 400 parts per million of calcium carbonate. Spoehr [7] has summarized the work of several investigators in this field, among them Russell [8] whose studies indicate that "when the air-supply is cut off, the carbon dioxide-content of the soil may rise to very high percentages. Thus, in India under monsoon-conditions Leather found that the carbon dioxide rose to 16-20 per cent." Very recent work by Smith [9] gives similar results, even for cultivated soils where the concentration of CO_2 cannot be as great as in forests and swamps where the soil is undisturbed.

There seems to be little doubt that soil-air as such is adsorbed on soil-particles and that CO_2 in particular may be selectively adsorbed. Chapek and Kuron [10, 11] have studied the phenomena of air-adsorption by soil-particles. Kuron showed that the adsorption of CO_2 on soils and clays follows Freundlich's adsorption-isotherm ($x/m = kp^{1/n}$, where x is the amount adsorbed by a mass of soil, m, at a pressure, p, and n is an integer). Chapek's analysis of the air adsorbed by soil-particles showed that its composition was similar to that of atmospheric air but that, in the lower layers, the air adsorbed by the soil is under a pressure of five to 15 atmospheres.

Water present in the soil will produce two results. It will reduce the soil-ventilation and so prevent the escape of CO_2 by diffusion and it will dissolve both the free gas CO_2 and adsorbed CO_2. Since the concentration of CO_2 in free soil-air and in the adsorbed soil-air is considerably higher than that in the atmosphere, the concentration of CO_2 in the soil-water will be relatively higher.

Several investigators [12] have studied the effect of rain on the soil-air content of CO_2. The amount of free CO_2 showed a considerable decrease according to Lehmann. On the other hand, Minar [13] found that the total CO_2-content had been increased after a rain by 167 per cent due partly to diminished soil-ventilation.

Of the total CO_2-content of the soil a part may be lost by diffusion into the atmosphere; other parts may be spent in dissolving any $CaCO_3$ present or in combining with basic compounds. Also there is wide variation in the total CO_2 which is being produced constantly in the soil because of marked differences in organic content, acidity or alkalinity, ventilation, seasonal changes of temperature and precipitation, and many other factors. In spite of these losses and variations it seems clear that the soil generates CO_2 in sufficient abundance to yield enriched CO_2-water solutions of the appropriate dissolving effectiveness.

Retention of CO_2 in a supersaturated solution--The third step in the present discussion concerns itself with the maintenance of the enriched condition of the CO_2-solution as it travels downward from the CO_2-rich top-soil environment through the cracks and crevices in the bed-rock to the water-table. While it is possible that in some cases this enriched CO_2 soil-solution, en route to the water-table, may be in contact with air of the same CO_2-content as normal atmospheric air, in general it is more probable that the higher CO_2-content of the top-soil blanket will preserve the necessary partial pressure to prevent the escape of CO_2 from the enriched solution. Solvent action of this enriched CO_2-solution on calcium carbonate will begin in the top soil and will continue until the solution is saturated with respect to its CO_2 partial pressure.

Even though this enriched CO_2-solution should become supersaturated due to a lowering of the required partial pressure of CO_2 (as in contact with normal air), its supersaturation will be prolonged for the following reasons:

(1) Ostwald [14] has shown that the supersaturation of a solution by a gas occurs when the partial pressure of the gas is reduced and gas-nuclei are absent. The formation of gas-bubbles, permitting the escape of the gas, requires energy and acts to keep the solution supersaturated.

Even though a few bubbles are formed they act locally and their effect is lost after their escape from solution. That carbon dioxide will form such supersaturated solutions is evident when one removes the cap from a pop bottle--often with the loss of very little gas.

(2) The rate of escape of CO_2 from a supersaturated solution depends upon the rate of diffusion of dissolved CO_2 to the surface of the liquid [15]. If the solution were in a shallow dish the escape would be more rapid than in a tall cylinder. In the latter case it may take weeks or even years to reach equilibrium. Ground-water conditions are in general comparable to the latter illustration. Even when ground-water comes in contact with normal air as in caves and springs it precipitates its calcium carbonate reluctantly. Most of the discrepancies in the literature on the solubility of calcium carbonate in carbonic acid can be attributed to the slowness with which equilibrium is reached.

(3) The precipitation of calcium carbonate from solutions containing calcium bicarbonate is an endothermic reaction. Since the effect is to cool the solution, rendering the calcium bicarbonate and dissolved CO_2 more soluble, the precipitation will be retarded.

(4) R. Stumper [16] has shown that the presence of colloidal dispersions protect and retard the decomposition of calcium-bicarbonate solutions. The colloidal character of most soils is well known, and the presence of colloidal particles in soil and ground-water is common.

(5) R. Stumper [17] has also shown that the decomposition of calcium-bicarbonate solutions begins only after a certain germination-period. The rate of decomposition following this germination-period increases as the concentration of calcium-bicarbonate decreases. It also varies as the square of the concentration of the bicarbonate ion showing that the decomposition is bimolecular. He thus concludes that the following equilibrium regulates the velocity of decomposition: $2\,HCO_3^- \rightleftarrows CO_2^{=} + H_2CO_3$. Under supersaturated conditions of ground-water the velocity of this reaction to the right is very slow, particularly at the temperatures of ground-water; hence it helps to account for prolonged supersaturated conditions in ground-water.

Although the blanket of top-soil concentration of CO_2 may vary considerably from place to place, and any movement of the ground-water may bring it under areas where the CO_2-content is low, resulting in supersaturation, yet the factors mentioned above operate to prevent the general precipitation of calcium carbonate and loss of CO_2 from ground-water.

Summary--To explain observed ground-water concentrations of calcium carbonate in limestone-terranes it is necessary as shown by the solubility-relations of $CaCO_3$ to account for a higher concentration of CO_2 in ground-water than can be explained on the basis of contact of water with normal atmosphere. This paper has indicated that a richly generating CO_2-environment exists in the soils containing bacteria, vegetation, and decaying organic matter. Water moving through this CO_2-rich zone dissolves CO_2 in accordance with its solution coefficient. It tends to retain its concentration, even though it may enter conditions where it is supersaturated, for several reasons, namely, the high energy required to permit escape of the gas, the slowness of diffusion of the gas to the surface-layer, the endothermic nature of the reaction, the retarding effects of colloidal particles, and the slow rate of decomposition of the bicarbonate ion. Ground-water, with relatively high CO_2-content thus retained, may travel to and through bed-rock crevices and is an effective agent in dissolving limestone, in enlarging openings, and in forming caverns, as well as transporting $CaCO_3$ in solution.

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SNOWFALL AND RUNOFF IN THE CANADIAN COLUMBIA BASIN: A STUDY TO DETERMINE THE IDEAL LOCATIONS FOR SNOW-SURVEY STATIONS

R. C. Farrow

Because of the absence of the author, this paper was abstracted only for the Washington meeting. It was communicated in full by him at the regional meeting in Denver and therefore appears in these Transactions under the proceedings of that meeting.

AMERICAN GEOPHYSICAL UNION

Regional Meeting, 1937

SECTION OF HYDROLOGY

Denver, Colorado
June 21 to 24, 1937

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OBJECTIVES OF THE SECTION OF HYDROLOGY

J. E. Church

The Earth and the Universe. What a progeny of scientific children they, or rather the former, have created. For from the Earth have come the sciences of air, land, and water, named meteorology, geology, and hydrology. And each in its turn has become specialized and yet cooperative. Their family-tree is as interlocked as that of the human race, for practical needs or human ambitions rather than reasoning have been at the base of their development.

In the beginning both geology and astronomy taught meteorology. They had equal claims. Then meteorology taught hydrology, for precipitation was apparently from the heavens. Now hydrology is becoming independent and oceanography has created a complex world of its own. At the present time meteorology, hydrology, and oceanography are oscillating between independence and interdependence, with the latter gaining the mastery.

Practically meteorology has gone heavenward and hydrology earthward. The former is specializing in the forecasting of weather, the latter in the effect of water. The fields necessarily overlap. Officially the study of water is apportioned between the meteorologists, geologists, engineers, and conservationists.

The United States Weather Bureau has retained precipitation and floods. The United States Geological Survey has taken stream-flow and underground waters. The engineers are forecasting water-supplies. The conservationists desire to improve them. Since measurements of precipitation have naturally become congested in the centers of population, where measurements are easy, rather than in the centers of hydraulic need, forecasting of water-supplies is becoming the acknowledged field of the engineers. However, the necessity for efficient cooperation calls for a guiding Division of Water Resources, such as has already been organized in some of the states.

Yet even here two broad fields persist: (1) The pure science of hydrology, and (2) its engineering applications. Some men toil in both. This is the reward of the college teacher. It is difficult to sever the fields. Pure science inevitably becomes human and applied, for it springs solely from the human viewpoint. Unfortunately the what or "applied" too often precedes the why. This is doubtless the cause of the founding of the International Union of Geodesy and Geophysics and its child, the American Geophysical Union--that is, to give aid and comfort to the theorists. In this broad division of the physics of the Earth lies the Section of Hydrology ("Scientific Hydrology" by International designation) in close association with its kindred sciences, meteorology and oceanography.

The subdivisions of the Section of Hydrology represented by Research Committees are more numerous and detailed than in the International Association of Scientific Hydrology, where they are known as Commissions. They are designated as: (1) Rainfall; (2) Snow; (3) Glaciers; (4) Evaporation; (5) Absorption and Transpiration; (6) Runoff; (7) Physics of Soil-Moisture; (8) Underground Waters; (9) Dynamics of Streams; (10) Chemistry of Natural Waters. Originally Rainfall and Runoff were one Committee. Runoff has been separated because it is a triplet rather than a twin. The International Commissions are very broad and comprise great natural features, such as: (1) Rivers; (2) Lakes; (3) Glaciers; (4) Underground Water; (5) Practical Applications; (6) Snow. The last one--Snow--is plainly an afterthought and a "raw material." In the Hydrologic Conference of the Baltic States there is also a division of Moors or Boglands, for these also are a dominant feature of northern Europe.

The American subdivisions could be condensed into the three sections of: (1) Runoff; (2) Underground Waters; and (3) Chemistry of Natural Waters. A step in this direction has been taken by Precipitation, Snow, Glaciers, Evaporation, and Runoff. The International Commission of Rivers has been put under Runoff, and that of Lakes under Evaporation.

The great variety of subjects possible under these few classifications is shown by the present program, which has won full recognition by the Executive Committee of the Section and acceptance by the Program and Publications Committee for printing in the Transactions.

The program can be summarized as follows. Out of some 40 papers, there are ten themes with the following rating, based on the number of papers in each: Use of water, 12; snow-surveying, 11; general, 4; floods, 4; underground waters, 3; precipitation, 2; normals, 1; forecasting, 1; erosion, 1; and ice on highways, 1.

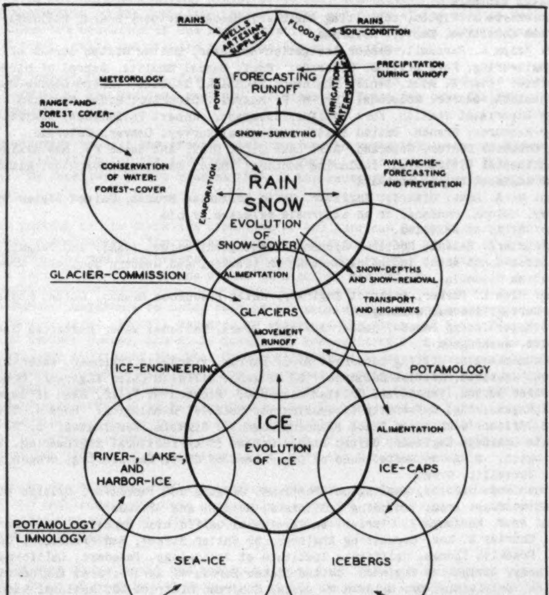
This is a broad program. Yet it is special to this Western Region. Indeed the West is the native laboratory of hydrology. In a trip to study Western watersheds in 1935, enough projects in forecasting stream-flow were found to bring the total of such projects to 22.

The specialty of the West is perhaps snow. The life of the semiarid West depends upon it. The extent of its relationships is shown by the specialties of the personnel of the Committee on Snow: Snow-surveying; water-supply forecasting; evaporation of snow; conservation of snow; rainfall; high mountain-snow; glaciers; water-power; flood-control; floods; snow-removal; snow- and ice-engineering; instruments; snow-sports; physics of snow; runoff; normals; International snow; arctic; and antarctic.

If combined with ice, snow comprises fully one-half of the raw material for problems in hydrology. This is shown in Figure 1 prepared for the International Commission of Snow.

For this practical reason, the International Association of Scientific Hydrology does not look with favor upon the formation of a new and independent International Association of Cryology (cold) dividing the field with meteorology, hydrology, and oceanography. Dr. Dobrowolski has sponsored this plan for years and has received permission to present it for final decision at the Triennial Meeting at Washington, D. C., in 1939. His argument is based on the physical properties of snow and ice as distinguished from those of rain. He believes also that the breadth of the world field justifies this. Nationally one arm of hydrology would be severed from the other.

Our meeting today represents a second geographical step in the development of hydrological interest. Owing to the dependence of the American Geophysical Union upon the Federal departments


RAINS
WELLS ARTESIAN SUPPLIES
FLOODS
RAINS
SOIL-CONDITION
PRECIPITATION DURING RUNOFF
METEOROLOGY
POWER
FORECASTING RUNOFF
IRRIGATION
WATER-SUPPLIES
RANGE-AND-FOREST COVER-SOIL
SNOW-SURVEYING
CONSERVATION OF WATER: FOREST-COVER
EVAPORATION
RAIN
SNOW
EVOLUTION OF SNOW-COVER
AVALANCHE-FORECASTING AND PREVENTION
GLACIER-COMMISSION
ALIMENTATION
SNOW-DEPTHS AND SNOW-REMOVAL
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MOVEMENT RUNOFF
ICE-ENGINEERING
POTAMOLOGY
ICE
EVOLUTION OF ICE
ALIMENTATION
RIVER-, LAKE-, AND HARBOR-ICE
ICE-CAPS
POTAMOLOGY
LIMNOLOGY
SEA-ICE
ICEBERGS
OCEANOGRAPHY
GLACIOLOGY
OCEANOGRAPHY

FIG. 1—VARIOUS PHASES OF INTEREST OF COMMISSION OF SNOW AND ICE AND THEIR RELATION TO OTHER COMMISSIONS AND ORGANIZATIONS

and scientific foundations at our National capitol, the Annual Meeting has been held continuously at Washington, D. C. However, Dr. O. E. Meinzer, first Chairman of the Section of Hydrology, organized a Pacific Coast meeting. A total of two meetings have been held. The present year Chairman Sherman and the Executive Committee approved the organizing of the Western mountain states and the adjacent provinces of Canada into four areas with a Regional Committee for each, empowered to call meetings whenever abundance of interest warranted or the presence of large scientific meetings made temporary affiliation feasible.

The boundaries are not fixed and temporary combinations for the purpose of holding meetings are recommended. The Regional committees, as in the case of other National committees, will hold office for the three-year period, granted to the general officers; and longer if reappointed by the new administration. Membership in the American Geophysical Union is not requisite to membership on the Regional Committee nor in fact on the Research Committees, though such membership is urged. Non-members are classed as "Cooperators." Canadians and others may be elected to membership in the Union in case they have been or are resident in the United States. No membership requirement is imposed for participation in the programs or for attendance at the meetings. This generous ruling makes full cooperation of all interests possible.

The Regional areas and committees are at present as follows:

Organization and personnel of Regional committees in the Western States for the holding of supplementary meetings in hydrology

(1) South Continental Divide Area, including Colorado, Wyoming, Utah, New Mexico, and adjacent states eastward

Chairman: Royce J. Tipton, Consulting Engineer, Member Advisory Board, National Water Resources Committee, Denver, Colorado

Members: Ralph L. Parshall, Senior Irrigation-Engineer, United States Bureau of Agricultural Engineering, Fort Collins, Colorado; Prof. Samuel Shulits, School of Mines, Golden, Colorado; Ivan E. Houk, Senior Engineer, Technical Studies, United States Bureau of Reclamation, Denver, Colorado; Dr. M. F. McArdle, Director, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado; Robert Follansbee, District Engineer, Water-Resources Branch, United States Geological Survey, Denver, Colorado

Meeting centers: Denver, Colorado; Salt Lake City, Utah; and Santa Fe, New Mexico

(2) North Continental Divide Area, including Montana, Idaho, Eastern Washington, Alberta, and the adjacent region eastward

Chairman: W. A. Lamb, District Engineer, Water-Resources Branch, United States Geological Survey, Helena, Montana, or an alternate selected by him

Members: Yet to be selected.

Meeting centers: Helena, Montana; Spokane, Washington; Boise, Idaho; and Calgary, Alberta

(3) North Pacific Coast Area, including Washington (Central and Western Section), Oregon, and British Columbia

Chairman: Glen L. Parker, District Engineer, Water-Resources Branch, United States Geological Survey, Tacoma, Washington

Members: Major Joseph Jacobs, Member Advisory Board, National Water Resources Committee, Seattle, Washington

Suggested members if willing to serve: R. C. Farrow, Hydraulic Engineer, Water-Rights Branch, Victoria, British Columbia; C. E. Webb, Division Chief Engineer, Dominion Water and Power Bureau, Vancouver, British Columbia; Richard G. Tyler, Head of Department of Civil Engineering, University of Washington, Seattle, Washington; Ross K. Tiffany, Executive Officer, Washington State Planning Council, Olympia, Washington; L. T. Jessup, Associate Drainage-Engineer, United States Bureau of Agricultural Engineering, Yakima, Washington; C. A. Mockmore, Head of Department of Civil Engineering, Oregon State College, Corvallis, Oregon

Meeting centers: Seattle, Washington; Portland, Oregon; and Vancouver, British Columbia

(4) South Pacific Coast Area, including California, Nevada, and Arizona

Chairman: Prof. Morrough P. O'Brien, University of California, Berkeley, California

Members: Charles H. Lee, Consulting Engineer, 58 Sutter Street, San Francisco, California; Prof. Franklin Thomas, California Institute of Technology, Pasadena, California; Harry F. Blaney, Irrigation-Engineer, United States Bureau of Agricultural Engineering, Los Angeles, California; Dr. Baldwin M. Woods, Chairman District 10, National Resources Committee, Berkeley, California; Charles J. Kraebel, Senior Silviculturist, California Forest and Range Experiment Station, Berkeley, California

Meeting centers: San Francisco and Los Angeles, California, or adjacent centers

The Vice-Chairman of the Section of Hydrology is ex-officio member of all Regional committees.

The vision, the wisdom, and the spirit of the various groups are assurance of success. The comments of the Chairmen make a vivid composite picture of the whole.

Comments

(1) South Continental Divide Area--Chairman Tipton writes: "To me, there is no more interesting area from the standpoint of Hydrology than the Rocky Mountain Region." The tentative program has been built largely around problems pertinent to the Rocky Mountain Region and irrigated portion of the United States.

(2) North Continental Divide Area--The Northwest Scientific Association has offered both a meeting place and a share on its program to the Regional Committee whenever meetings are held at Spokane, its permanent place of meeting.

(3) North Pacific Coast Area--Chairman Parker writes: "Interest in the application of hydrological data and in hydrological research has not been great in the Pacific Northwest but the problems involved have become fairly well recognized through activities of the Water Resources Committee of the National Resources Committee, in which Major Jacobs has taken such an active part. He thinks, as I do, that we should not seek a large membership in the proposed Regional Committee and that it would be unwise to meet more often than once a year unless in conjunction with a meeting of some other allied organization. We feel that it would be better to appoint on the Committee at the outset only those whose interest in hydrological investigations is keen. Later on a more aggressive campaign might become profitable. In the meantime, the Committee could act as spokesman for the Section in promoting hydrological research and could encourage participation by the various Federal, State, municipal, and private agencies.

"As to membership on the Committee, Major Jacobs and I are of the opinion that for the present at least the selection of one representative from each of the larger institutions of learning and other public and private organizations will suffice."

(4) South Pacific Coast Area--The Regional Committee in this area has been selected for its successful conduct of two Regional meetings. Professor O'Brien has been Chairman in connection with both meetings.

The opportunity to call the present meeting arose in connection with the Summer Session of the American Association for the Advancement of Science, which has granted full privileges of affiliation. So excellent is the program that it has received the following praise from Chairman Sherman:

"At the meeting of the Executive Committee of the American Geophysical Union on May 26, the following action was taken: 'The proposed Regional Meeting of the Section of Hydrology at Denver was approved. It was also ordered that the papers and reports submitted at that meeting be printed as a part of the Transactions of the 18th Annual Meeting.'"

A Snow-Survey Conference is being held of all snow-surveyors and cooperators in the South Continental Divide Area. Merrill Bernard, in charge of thr River and Flood Division of the United States Weather Bureau, and R. S. Goodridge, representing C. E. Ramser, in charge of Watershed and Hydrologic Studies of the Soil Conservation Service, have come especially to share in the deliberations. The River and Flood Division seeks to extend to the Eastern Mountain states the Federal-State Cooperative snow-survey service now covering the West and already established as State and private services in Eastern Canada, New England, and New York. The Soil Conservation Service desires to employ snow-surveying in shallow snows in connection with its watershed studies. R. C. Farrow, representing the Comptroller of Water Rights of British Columbia, will give us a research picture of forecasting the flow of the Canadian Columbia.

But forming the foundation of the sessions are Federal, State, municipal, and private organizations and individuals who have generously accepted a routine share in the work. Chairman Sherman and other members of the Executive Committee have come to formalize, that is, to vitalize, the Western meetings.

The three-year objective of the American Geophysical Union is to prepare to be hosts to the International Union of Geodesy and Geophysics at its meeting at Washington in 1939. The Section of Hydrology is particularly interested in the division of the Union known as the International Association of Scientific Hydrology. Its various commissions have proposed the following topics for analysis and presentation:

(1) Commission of Potamology (Rivers)
- (a) The preparation of a memorandum on the present state of work on evaporation, based on an inquiry to be made of the Government and other organizations concerned.
- (b) The forecasting of floods, having special regard to observations of rainfall, of snow-cover and of atmospheric conditions, and, if possible, weather-forecasts. Concrete examples of practical applications.
- (c) The study of the conditions of transport of solid load in streams with a bed of loose sediment (alteration of the shape of the bed-formation of banks, sills, and deeps, namely, deposition and erosion). Laws of transport of material, especially with regard to the speed and depth of the water and to the specific gravity and dimensions of the material, obtained from laboratory-tests and from direct observation of natural streams.

(2) Commission of Limnology (Lakes)
- (a) The study of the temperature ruling in lakes, particularly with the assistance of public services and electrical companies operating on big dams. Information to be obtained by the National Committees from the above-mentioned services and companies.
- (b) The study of the formation and dissipation of ice on lakes.
- (c) The preparation of a list of non-biological, limnological research works based on an inquiry to be made from interested institutions or authorities in the various countries.

(3) Commission of Subterranean Waters
- (a) The circulation of water and of water-vapor, also the condensation of the latter, between the surface of the ground and the zone of saturation.
- (b) The definition of the various kinds of subterranean waters.
- (c) The determination of the runoff and of the physical conditions of flow of subterranean waters in natural and in altered ground, the circulation being natural or induced. The preparation of a world census of subterranean waters, their characteristics, and the use made of them. The preparation of a list of scientific works on them in all countries, including those which do not belong to the Union. The results of this inquiry will be presented at the Assembly of 1939.

(4) Commission of Snow
- (a) The permeability of snow with respect to water. The capacity of the snow to retain water.
- (b) Influence of snow and ice on the flow of streams, allowance being made for frost in the ground and for condensation.
- (c) Compilation of snow-maps of all countries.

(5) Commission of Glaciers
- (a) Study of variations in size of glaciers.
- (b) Respective roles of rime, hoarfrost, and wind-blown snow in the equilibrium of glaciers.
- (c) Sounding the depth of glaciers.

Here is a world challenge to research. All member countries of the Union are urged to enter. Secretary Stakle of the Commission of Snow writes urgently. His is a tiny country on the Baltic but his personality is international. Says he: "Thus the Commission of Snow will really become the 'clearing-house of information and the advisor in methods', as you have written. And the Washington meeting would become the parting of ways in the science of snow and ice."

There are also no restrictions in the International Commission of Snow to active participation on the part of all in its research work, nor probably are there any restrictions in the others. Results rather than membership are sought. The former will bring the latter.

This time, owing to the geographical isolation of the Americas, the meeting becomes intercontinental as well as international. The Americas have a large opportunity and duty as hosts. They should not fall behind in the program.

Nevada Agricultural Experiment Station,
Reno, Nevada

HYDROLOGY AS A SCIENCE

L. K. Sherman

Hydrology, as one of the geophysical sciences, deals with water derived from rain and snow in its movements over and underneath the surface of the Earth. This movement and storage of water is essential to life. It is the prime factor which governs all human and economic developments.

It is, therefore, natural that civil engineers, and not scientists per se, were the first to attempt to discover, as a matter of practical utility, the relation between precipitation, stream-flow, reservoir-storage, and underground water-supply. The engineer has to be a prophet in order to design, in advance, a storm-sewer, a reservoir, or the summit water-supply for a canal. Unlike electricity, for example, he had no pioneers in pure science who had cleared the wilderness preparatory to his apparatus and his structures. In hydrology, the engineer used the most direct methods. They were generally empirical, often crude and inconsistent. Sometimes he did very well.

I do not need to apologize to engineers for anything I say here. I am one of them. They have done more for the development of quantitative hydrology than has any other group. I am not here forgetting the good work of the geologists and I am not mad at the foresters because one of them said: "If engineers are permitted to dominate flood-control, then we shall have bigger and better floods."

With the years came the important work of collecting basic data by the Water-Resources Branch of the United States Geological Survey, the United States Weather Bureau, and the Bureau of Reclamation. Collection of data is not, and never will be, complete. It is essentially a continuing operation; it needs amplification in many directions. Data are essential to science. But data alone, and by themselves, are quite useless. They need correlation and interpretation. They need the why and the wherefore. In this interpretation, the hydrologist becomes the explorer and the discoverer.

The scientist is not primarily interested in any special economic attainment. His search is for the truth, with the realization that all such knowledge is essential to sound engineering and practical applications.

The Section of Hydrology of the American Geophysical Union was formed at a meeting in Washington in May, 1930. Now, in its seventh year, it has a membership of about 450 of the country's leading hydrologists. It is the United States Member of the International Association of Scientific Hydrology.

While several of the engineering, geological, and meteorological societies, as well as other organizations and individuals, have made valuable contributions to the advancement of hydrology, this Section, started in 1930, is the one group in the country devoted to hydrology as a science.

In 1939, we shall be host to the hydrologists of the world at the triennial conference of the International Association of Scientific Hydrology. Many of these foreigners will visit the Western and Pacific Coast States. I call them "foreign." So far as country goes--yes. So far as individuals are concerned, they are "brother hydrologists," interest and with the same objectives that we have.

In this hectic world today, with all its bickerings, jealousies, and hatreds, there is only one International Brotherhood, and that is the Brotherhood of Science.

During the last few years, the United States has witnessed a greater nation-wide interest in hydrology than has heretofore existed during many decades. A part of this is due to the occurrence of severe floods, drouths, and storms, coupled with the greater population and structural development. The program of this Colorado Meeting of the Section of Hydrology reflects this interest in the work of hydrologists in all branches. It also reflects great credit to the energy and ability of Chairman Royce J. Tipton and his Colorado Regional Committee.

The program of this Meeting describes some of the works, problems, and contributions toward a more effective use of the Science of Hydrology by the State and the several Federal departments. The contributions to Hydrology by two new Federal agencies, the Soil Conservation Service, and the Water-Resources Division of the National Resources Committee, are well known and appreciated by you. For the record here, I simply note that, for the first time in our history, the water-resources of the entire nation have been considered comprehensively and upon the relative merits of divergent utilization.

With reference to our future activities, I will comment upon one line of hydrologic research which I deem of first importance. The time has now come when we should discard the general use of the time-honored "coefficient of runoff." The use of this convenient expression of our ignorance of the relation of runoff to precipitation is not scientific hydrology. The runoff-coefficient varies from zero to 100 per cent with rain, and more than that with snow. It is a variable with season, antecedent precipitation, duration and intensity of rain, nature of the soil, characteristics of basins, vegetation, etc. The engineers, with nothing better at hand than the coefficient-formulae for runoff, condoned the situation with the statement that runoff is erratic and that old man experience has become a pretty good guesser.

With the exception of certain average conditions, the runoff-coefficient should be superseded by the relation that surface-runoff equals precipitation minus losses. The qualitative phenomena and the procedure for the determination of infiltration-rates and other losses are fairly well established. This is not generally known or appreciated. Maybe that will have to await the time when it is abstracted from our scientific periodicals and put into text-books on engineering hydrology. But I do not put this audience in the "generally known" class. You, as scientists, are now the advance guard.

This application of infiltration and other losses requires quantitative analysis and quantitative measurements. Much work is needed in order to determine definite rates of infiltration, on various basins, with various seasons, and with various conditions of antecedent precipitation and soil-moisture. Quantitative analysis deals with the specific, not with generalities. Most of the hydrologic phenomena are coincident with many varying conditions and effects; some are positive, and some are negative. By laboratory and field-plot tests, such effects may be segregated so that complex phenomena become simple, and we are then enabled to assign proper relative values to the different factors. It is not sufficient to say that we find that surface-runoff is reduced or that infiltration is increased by certain soil-conditions or by certain vegetal cover. The question must be answered: When? How much? One-hour storm or six-day storm? Without this we have a part truth and an extrapolated truth may be erroneous.

We need something more than the records of the United States Weather Bureau for total 24-hour precipitation in order to determine infiltration-rates. The rates and duration of rainfall during a storm are essential. For this purpose, the hourly records of rainfall, now furnished for a few stations by the United States Weather Bureau, should be greatly increased. Recording gages should be distributed so that the intervening 24-hour station records may be fairly prorated on an hourly basis by the hydrologist. Specific notations should be made in the Weather Bureau publications of stations served by self-recording gages. These same remarks apply to stream-gaging stations listed in the United States Geological Survey Water-Supply Papers.

The right approach to the unknown has no sign-board. The investigator in science finds many blind alleys. The log of exploratory research, based upon a reasonable hypothesis, often ends in the waste-basket. The only accomplishment (and it is an accomplishment) is the answer: "This is not the way." But all truth and all science is in harmony. It is one of the gratifying features of our work that, if we are on any one of the right approaches, we eventually meet and concur with our fellow workers.

53 West Jackson Boulevard,
Chicago, Illinois

HYDROLOGY IN THE AMERICAN GEOPHYSICAL UNION AND IN THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

N. H. Heck

It is with great interest that I am attending the first meeting that any part of the American Geophysical Union has held outside of Washington, D. C., and California (the latter only in the case of the Section of Hydrology). In the case of the other sections there are reasons aside from a certain conservatism why meetings should be held only in Washington. In the case of Hydrology the situation is different and I believe that there is no better way to deal with existing problems, and to find means of attack on new ones, than to hold meetings throughout the country which can be attended by interested groups of effective size.

As regards the American Geophysical Union, tne Section of Hydrology is fairly new, having been established in 1930, though the rest of the Union dates from 1919. One of the reasons was that the Union was originally a committee of 100 and expansion did not seem desirable. When all limits were removed, the development of the Section of Hydrology, which was in the hands of a special committee for several years before the actual formation, was logical, though the rapid growth came as a surprise.

At first there was perhaps some apprehension that there might be a large number of members interested only in one Section or that the large numbers might undertake to dominate the Union in a manner which the older sections would not like, but these proved unjustified and the only feeling on the part of the non-hydrologists at present is satisfaction with the high aims and progressiveness in the Section of Hydrology and recognition of the important national service which it is performing.

Many of you are undoubtedly interested in the problem of publication. The present method achieves the almost impossible--to place before the members, at a cost within the limited resources of the Union, the very large amount of material presented at the various meetings. To be sure, there have to be additional contributions especially from the hydrologists, but the general results are satisfactory. However, there is a strong demand for a Journal of Geophysics. A Committee with a representative from each Section has the matter in hand with well-developed plans, but funds are still insufficient.

As Chairman of the Union, I would like to express one hope. The Union has several very effective committees relating to more than one Section, notably those dealing with the geology of the continents and oceanic basins. It would be very desirable if in the course of time the very excellent committee organization of the Section of Hydrology were extended to the participation in joint committees. There are obvious relations with meteorology, but others exist. In this connection, the Union has just established a Planning and Project Committee whose duty will be to outline desirable projects in the field of the Union with the view that the very expression in concrete form of the needs may lead to finding means of execution.

To come to international matters, the International Union of Geodesy and Geophysics grew out of pre-war organizations in Geodesy and Seismology, which usually met in either Germany or France. The committee which met in Belgium in 1920 provided for sections of Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, and Volcanology. Two years later at the Rome meeting, the Association of Scientific Hydrology was formed. It may not be known to you that, besides being a Section of the American Geophysical Union, your Section is the American branch of the International Association of Scientific Hydrology and your officers in international scientific matters relating to hydrology deal directly with those of the international organization and not through the General Secretary of our Union though he very properly expects to be kept informed of such communications so that no misunderstandings may arise.

The International Association consists largely of heads of hydrological organizations within the several countries (in all 33 nations adhere to the Union) and is an effective organization. Its meetings have not been entirely satisfactory from the viewpoint of the English-speaking member, but this is largely due to the fact that participation by the English-speaking nations of Europe has been limited and American participation did not begin until 1936 when the Edinburgh Assembly was attended by Messrs. Meinzer, Church, McLaughlin, and Elges. There is excessive use of the French language as compared with the other associations. However, such matters will readily be adjusted with increased participation from this country.

You are aware that the next meeting will be in Washington, D. C., in the fall of 1939. It is possible that our spring meeting will be omitted that year so that those from a distance will not have to choose between two meetings and so divide their effort. The Union is taking on a considerable project but it expects a full return. It will be the most worth-while event of a geophysical nature that has ever taken place in this country. It might seem at first thought that, if the Union is unable to undertake a journal, it should not take on an international meeting, but the Executive Committee believes that the two things are not directly related and funds available for one would not be forthcoming for the other.

I do not have time to go into great detail, but I hope you will realize that the Washington Assembly is your meeting and that you are going to be hosts to the hydrologists of many other countries. I hope also that it may be possible to show them at first hand some of the very interesting work that hydrologists are doing in this country.

U. S. Coast and Geodetic Survey,
Washington, D. C.

HYDROLOGIC ASPECTS OF FLOOD-FORECASTING

Merrill Bernard

Recently, an effort to consolidate existing knowledge in the field of small-stream control through the medium of a national conference evoked much editorial comment. Particularly did the newly coined term "upstream engineering" seem objectionable for it implied distinctions, many insisted, which were more superficial than real.

Quite true it is that basic hydraulic laws apply equally to water flowing in the headwater rivulet and in the outflow reach of a large river. In many respects, however, there are practical differences which would seem to justify a division of the field. Among them are:

(1) The difficulties of relating stream-flow to the precipitation producing it on basins larger than storm-areas over which rainfall is sufficiently well distributed to give dimensional significance to average rainfall-depth.

(2) Flood-flow problems at headwaters are, to a great extent, involved in the creation and translation of waves propagated and sustained by innumerable contributions throughout the combined length of the channel-system, differentiating from conditions of flow on the lower reaches where contributions to flow are concentrated at relatively widely separated points.

(3) Generalizations in stream-flow problems are difficult if not impossible because of great differences in the ranges of slope, channel, and storage-factors, concentration-periods, and related rainfall-coefficients.

(4) Methods of stream-control tend to associate land-use and small storage with "upstream" problems while problems downstream are characterized by large storage- and protection-works.

(5) The differences in technique best suited to the solution of flow-problems are analogous to the distinctions between the sciences of hydrology and hydraulics--the former being associated with headwater-areas, the latter with lower-stream projects.

(6) Local responsibility and participation in cost is an important consideration in upstream problems, in many cases overshadowing Federal and State interests.

These distinctions are found to have marked effect upon the operations of the River and Flood Service of the Weather Bureau. Here time is a principal element and the problems of forecasting divide themselves rather abruptly at a point on a river where there remains sufficient time after the flood is created in the principal channel above, to make an estimate of maximum stage and the hour of crest-arrival at forecasting centers, broadcast the warning, and organize for evacuation and relief.

For downstream reaches of the stream methods of forecasting are based largely on stage relationships, the accuracy and dependability of the forecast increasing as the mouth of the river is approached, as does the opportunity to prepare unprotected areas for high water and to organize relief. It is expected ultimately that lower-river forecasting will become an integrated flow-assembly based upon an improved knowledge of river-hydraulics, particularly the propagation of flood-waves and channel-storage adjustment.

Progressing upstream the method of forecasting is dominated by hydrologic rather than hydraulic factors. Advantage must be taken of the collection-period for the basin, which, added to time of translation through the channel-system, constitutes the maximum forecasting period--in many cases a matter of hours and not days.

At headwaters and on small river-basins the method of forecasting is evolved through the following steps:

(1) The establishment of rainfall and stream-flow records of short duration--It is now generally recognized that rainfall-depth observed at 24-hour intervals and considered as an average rate for that duration, is not applicable to watersheds of less than 500 square miles. Also stream-flow recorded as a 24-hour average can not reflect the variations to be expected on small watersheds. The unit of time should obviously not exceed the concentration-period for the particular watershed. It is necessary, therefore, to establish recording gages for rainfall and stream-flow over the river-basins and headwater-areas to be studied in sufficient number, and so located as to give an accurate knowledge of rainfall and runoff for all durations. The need for

such a source of data in the immediate plans for an improved forecasting-service is threefold. First, in the development of a rational method of stream-flow determination in which the runoff-characteristics of each sub-watershed are to be expressed quantitatively as a distribution-graph or flow-combination; second, in identifying those sub-basins which have the quality of reflecting ground-surface conditions and runoff producing characteristics for the whole of the basin and therefore can be used as indices of conditions antecedent to flood-producing rainfall; and third, in furnishing to the forecaster an hour-by-hour knowledge of the areal distribution of a rapidly accumulating rainfall-depth over the basin.

Headwater-forecasting methods, based as they must be upon rainfall-runoff relationships, can only follow the establishment of adequate sources of hydrologic data.

(2) Hydrologic studies and development of method--Recent years have given impetus to the development of methods for estimating stream-flow from rainfall. The work of L. K. Sherman, Robert E. Horton, W. W. Horner, and others have made it possible to estimate accurately from rainfall not only peak-flow but the hydrograph of flow. While these methods await the results of basic research to become wholly independent of empirical factors, they offer the first opportunity to inaugurate a practical forecasting-service in many localities and promise refinement in method for certain others.

(3) The establishment of hydrologic forecasting-centers--Although the Weather Bureau has for many years conducted with regularly employed personnel on the larger rivers an accurate and dependable forecasting-service, complexities at headwaters and on important small basins have made it necessary to organize a special service, which involves operations comparable in certain respects to modern train-dispatching. Procedure at a typical headwater forecasting-center will in general be as follows:

(a) A day-by-day estimate of runoff-potentialities based upon the discharge from index-watersheds, the estimate to include the possible contribution to runoff from an existing snow-mantle.
(b) A day-by-day check on storm-approach, utilizing the more practical phases of air-mass analysis.
(c) With the beginning of a critical storm-period the reception of hourly (or other period) rainfall by telephone and telegraph, or by amateur and automatic radio broadcasting.
(d) The preparation of an isohyetal map showing the progressive accumulation of rainfall-depth over the basin.
(e) Under a well-organized and largely mechanical technique, the conversion of rainfall into stream-flow hydrographs.
(f) The conversion of rates of stream-flow into river-stage at points downstream for which a forecasting-service is rendered.
(g) As quickly as rainfall has ceased, the prompt announcement, through established channels, of flood peak-stage and the hour of crest-arrival.

Plans for an expanded and improved forecasting-service are well advanced. The Weather Bureau, in cooperation with the Geological Survey and the State of Pennsylvania, is organizing such a service on the Allegheny, Monongahela, Susquehanna, and Delaware river-basins. Under the plan approximately 100 recording rain-gages are being established in this region and the Geological Survey's program is being supplemented with additional stream-flow stations. Also a hydrologic study for the purpose of developing forecasting-methods has been established at Harrisburg, Pennsylvania. A unique feature of this project is the employment of hydrologic engineers who will travel over established circuits, on schedule, attending and servicing the recording rain-gages. During the winter these engineers will be engaged in snow-surveys. Other plans for expansion and improvement of service are:

(1) The division of the country into eight hydrologic regions within which the forecasting and flood-warning service will be extended to all important points on the principal streams of the region.
(2) The unification of forecasting-methods on the larger rivers and their adjustment to the Army's plans for river-regulation.
(3) In conformity with adopted plans for basin-studies and flood-control, the installation of a network of recording rain-gages over the Mississippi River Basin. The plan provides for approximately one thousand gages each representing from 500 to 1000 square miles.
(4) In collaboration with the Corps of Engineers, the establishment of a hydrologic research-project, which, among other objectives, will define regions of like storm-potentialities, synthesize and transpose limiting storms within these regions for the purpose of determining maximum flood-flows, establish zones of potential flood-hazard and test the practical applicability of certain meteorological concepts to hydrologic problems.

(5) The organization of snow-surveys throughout the central and eastern United States.
(6) The establishment of a comprehensive record of evaporation, nation-wide, and the development of regional factors for the conversion of loss from the standard evaporation-pan to that from a large water-surface.
(7) In collaboration with other interested agencies, improvement in method of gathering, evaluating, and publishing data on flood-damage.

The Weather Bureau, because of its far-flung facilities for gathering and transmitting meteorologic and hydrologic data, has a definite place in the operation and regulation of the nation's streams. It will appreciate support in meeting the rapidly growing demands entailed in that responsibility.

River and Flood Division,
U. S. Weather Bureau,
Washington, D. C.

THE NATIONAL RESEARCH COUNCIL INTERDIVISIONAL COMMITTEE ON DENSITY-CURRENTS

Herbert N. Eaton

(Published with the approval of the Director of the National Bureau
of Standards of the United States Department of Commerce)

The importance that has come to be attached in recent years to the silting of reservoirs is rapidly focussing attention on the phenomena that occur in such bodies of water. The fact that currents of silty water due to inflow at the head of a reservoir or lake may move as more or less clearly defined bottom-currents for long distances through the main body of clear, quiet water and so may carry at least the finer portion of the suspended load for long distances before dropping it has been recognized for some time. However, such a phenomenon is not easy to observe, and instances of it have passed practically unnoticed except in the infrequent cases in which the silty currents have passed entirely through the reservoir and issued through the outlet-gates at the dam. (Instances have been reported recently of the observation of such currents from airplanes.) A number of these muddy discharges have been observed at the Elephant Butte Reservoir [see 1 and 2 under "References" at end of paper], and more recently the passage of silty currents through Lake Mead has been reported [3].

Whether it will ever be possible to control currents of silt-laden water in reservoirs so that they may be forced to deposit their entire load of sediment in the reservoir or to pass a large portion of it through outlet-gates, as may be desired, is very doubtful. Nevertheless, it appears that no hope of controlling them, however faint, can be entertained until the exact conditions under which they can occur in any given reservoir are understood. And even if no measure of control is ever possible, the relation of these currents to the silting of reservoirs warrants making an attempt to understand the hydrodynamics of this phenomenon. It is not the purpose of this brief paper to attempt any scientific contribution to this subject but merely to call attention to the fact that a concerted effort is to be made along these lines and to point out the direction that certain laboratory-research now in progress has taken.

Somewhat more than a year ago, a Committee on Borderland Fields between Geology, Chemistry, and Physics was formed under the auspices of the divisions of Geology and Geography, Chemistry and Chemical Technology, and Physical Sciences of the National Research Council, with Dr. T. S. Lovering as Chairman. The purpose of this Committee was to review various borderline problems between geology, chemistry, and physics, the study of which was particularly important and timely, and the solution of which might be furthered by cooperative effort. A Subcommittee on Hydrodynamics was formed subsequently, with W. W. Rubey as Chairman, to consider problems of this nature that might be classified under hydrodynamics. This Subcommittee received recommendations from several different sources that studies be made of bottom-currents, with particular reference to their occurrence in reservoirs and lakes and on the sea-floor.

As a consequence of the interest shown in these currents, a recommendation was made through the main Committee to the National Research Council that it authorize the formation of a committee to study these currents and that this committee be sponsored by the divisions of Geology and Geography, Chemistry and Chemical Technology, and Engineering of the Council. The recommendation was approved, and the organization of the committee which is to be called the Interdivisional Committee on Density-Currents of the National Research Council is now in progress. The personnel, as far as selected, is as follows:

H. N. Eaton, Chairman, National Bureau of Standards, Washington, D. C.
M. M. Ellis, U. S. Bureau of Fisheries, Columbia, Missouri
N. C. Grover, U. S. Geological Survey, Washington, D. C.
P. V. Hodges, Bureau of Indian Affairs, Los Angeles, California
C. S. Howard, U. S. Geological Survey, Washington, D. C.
R. T. Knapp, California Institute of Technology, Pasadena, California
W. C. Lowdermilk, Soil Conservation Service, Washington, D. C., with G. C. Dobson (alternate), Soil Conservation Service, Washington, D. C.
H. Peters, Massachusetts Institute of Technology, Cambridge, Massachusetts
F. P. Shepard, University of Illinois, Urbana, Illinois
C. S. Scofield, U. S. Bureau of Plant Industry, Washington, D. C.
W. A. Snow, Board of Engineers for Rivers and Harbors, Corps of Engineers, Washington, D. C.
H. U. Sverdrup, Scripps Institution of Oceanography, La Jolla, California
C. P. Vetter, U. S. Bureau of Reclamation, Denver, Colorado
C. Juday, University of Wisconsin, Madison, Wisconsin
R. A. Daly, Harvard University, Cambridge, Massachusetts

The Committee held meetings at Washington, D. C., June 14 and 15, 1937, to organize a coordinated program of observations on several reservoirs by several bureaus of the Federal Government that are now taking observations on such reservoirs more or less independently. While the observations could be planned primarily for the purpose of studying the movement of silty currents of water through reservoirs, nevertheless they would be useful for many other purposes.

After a careful canvass of the possibilities, the Committee concluded that the greatest value would result from concentrating on a single reservoir in which currents of silty water were known to exist at times, and the Elephant Butte Reservoir in New Mexico was chosen as the one best adapted to the purposes by virtue of the occasional existence of flows of silty water and because of the fact that several governmental bureaus are now making observations there. A subcommittee was then appointed with C. S. Scofield as Chairman to draw up a program of cooperative observations, the latter to commence within a few weeks.

The observations as planned will include the volume and salinity of inflow and outflow of the Reservoir, periodical determinations of stratification of the water in the Reservoir as determined from temperature, salinity, turbidity, and other physical and chemical properties of the water, continuous records of temperature at several points along the bottom of the Reservoir, sampling the turbid water at several stations when currents of silty water pass through the Reservoir, measurement of light-penetration (turbidity), dissolved oxygen, hydrogen-ion concentration, carbon compounds, and a biological assay.

A somewhat less extensive program of field-observations has been drawn up for Lake Mead, and another subcommittee has been appointed with C. P. Vetter as Chairman. The United States Indian Irrigation Service has also agreed to take samples and, if possible, to measure temperatures at Coolidge Dam during flows of silty water.

While the interest in currents of silty water in reservoirs was the principal factor that led to the formation of the Committee, it is well known that density-currents play an important part in several other fields of investigation. (The following is proposed tentatively as a definition of density-currents: A density-current is the movement, without loss of identity by mixing at the bounding surfaces, of a stream of fluid under, over, or through a body of fluid, the density of which differs from that of the current, the density-difference being a function of the differences in temperature, salt-content, and/or silt-content of the two bodies of fluid.) It has been suggested, for example, that currents of heavily silt-laden water may have been responsible for the formation in past ages of the newly-discovered submarine canyons on the outer edges of the continental shelves [4]. This theory is receiving considerable attention from geologists at the present time, including several members of the Committee.

Another aspect of the problem having considerable economic importance is the gliding of fresh water over salt water, or salt water under fresh water, such as occurs in river-estuaries. Particularly at times of subnormal river-flow, the salinity in the upper reaches of estuaries tends to increase, and where, as in the Sacramento River Estuary, a considerable amount of water is used for irrigation, great damage can be done by the encroachment of salt water.

Limnologists also are interested in silt-laden currents of water because of their effect on fish-life, and observations on the stratification of water in lakes are now being made in several quarters from this point of view.

Another phenomenon in which the Committee may interest itself is the failure of the water from a tributary to mix with the water of the main river below the junction of the two streams. It is observed frequently, when the two streams are of different colors, that they will flow side by side for miles without mixing.

It is expected that two distinct lines of attack will be made on the problem of density-currents: (1) Field-observations to ascertain the actual facts relating to this phenomenon as it occurs in nature, and (2) theoretical and experimental laboratory studies to determine under what natural conditions such currents can exist. Both methods of approach must be utilized simultaneously, since field-observations alone will never furnish an explanation of the phenomenon, nor can any theoretical explanation be accepted without verification from field-observations, because of the complexity of the problem.

Theoretical and experimental studies of this problem have been in progress at the National Hydraulic Laboratory at the National Bureau of Standards for the better part of a year in an investigation of the following points proposed for consideration by the United States Geological Survey:

(1) The movement of water of one density through a body of water of a lesser density--the density being recognized as a function of temperature, of content of dissolved material, of content of suspended material, or of all three.
(2) The movement of water through the reservoir as influenced by the presence of an old river-channel at the bottom of the reservoir and by the presence of bars or other obstructions which might act as baffles.
(3) The raising of water having a slightly greater density from the bottom of the reservoir to an outlet a considerable distance above the bottom of the reservoir.
(4) The influence of the nature and quantity of dissolved material on the nature and quantity of suspended material that may be carried into and through a reservoir.

The theoretical attack on the problem has followed the lines of Prandtl's treatment of the stability of superposed fluids of different densities, and the criterion that he has established for determining whether mixing between superposed currents will or will not occur has been modified to apply to the present problem. Along with this study, experiments have been conducted involving the flow of a stream of water over a still body of a slightly denser salt-solution. One interesting result of the experiments was that under some conditions an intermediate fluid-layer of finite thickness appeared to form between the stream of water and the salt solution. The immediate need in connection with these studies is for reliable and adequate field-data to compare with the results obtained. At present it is not safe to predict from the laboratory-results what will happen in nature, since it has not yet been demonstrated that a true small-scale model of the phenomenon can be achieved.

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EUROPEAN HYDROLOGIC ACTIVITIES

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The manuscript for this paper was not submitted.

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WATER-TEMPERATURES IN RESERVOIRS

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Many investigations of water-temperatures at different depths in reservoirs have been made during the last 50 years, particularly in connection with the design of storage-works for municipal water-supply. Hamilton Smith, Jr., published a brief article on the subject in 1884, and Desmond Fitzgerald published a more lengthy article in 1895. Since that time several comprehensive papers on deep-water temperatures have been recorded in scientific literature. The bibliography appended hereto lists some of the more important contributions.

Data on reservoir-water temperatures are needed by hydraulic engineers, not only in studies of water-supply operation for domestic consumption, but also in the technical design of storage-works for all purposes, including power, irrigation, navigation, and flood-control, as well as municipal water-supply. This is especially true in the case of arch dams where temperature-stresses have important magnitudes and where concrete-temperatures near the upstream face of the dam are primarily dependent on reservoir-temperatures. Knowledge regarding water-temperatures is also necessary in the design of appurtenant dam-works, such as gates, valves, outlet-conduits, and penstock-pipes, where temperature-stresses may constitute controlling criterions in determining thicknesses and other details of design. Both pipe-temperatures and concrete-temperatures were important considerations in planning the 731-foot Boulder Dam, recently completed on Colorado River near Las Vegas, Nevada.

When detail-work was begun on the design of Boulder Dam, it was discovered that all available data on reservoir-water temperatures had been obtained in temperate and sub-alpine climates. No data were found which could be considered applicable to the comparatively hot, arid conditions existing near Las Vegas. Consequently, the Bureau of Reclamation began the measurement of water-temperatures at different depths in several reservoirs located in southwestern United States. These included Elephant Butte Reservoir on the Rio Grande in southern New Mexico; the Roosevelt, Horse Mesa, Mormon Flat, and Stewart Mountain reservoirs on Salt River in south central Arizona; and the Coolidge Reservoir on Gila River, also located in southern Arizona. Similar measurements were later begun at Owyhee Reservoir, eastern Oregon, where temperate climatic conditions prevail; and, still more recently, at Mead Lake, the reservoir created by the construction of Boulder Dam. The investigations at the Arizona reservoirs were made under a cooperative contract with the Salt River Valley Water Users Association.

Water-temperatures were measured with electrical-resistance thermometers, lowered by insulated cables. The observations were made once a month, usually at five-foot intervals of depth in the upper portions of the reservoirs and at gradually increasing intervals in the lower portions, where temperature-conditions are more constant.

Due to the great mass of data obtained, it is not possible to include herein a comprehensive analysis of water-temperature variations at the above-mentioned reservoirs. Furthermore, the fundamental relations between water-temperature and density, the characteristic settling of the heavier water to the lower depths, and the resultant seasonal turnovers in large bodies of water are well known and need no discussion. Consequently, this presentation will be confined to a few typical illustrations and a few special conditions which have not heretofore been observed in water-temperature measurements.

Figure 1 shows the data obtained at Elephant Butte Reservoir during 1935. The Reservoir was created by the construction of Elephant Butte Dam, completed in 1916. The Dam is 306 feet high above the lowest part in the foundation, approximately 200 feet high above the natural river-bed, and is provided with outlets at heights of about 20 and 75 feet above the river-bed. The Reservoir, which has a total storage-capacity of 2,638,000 acre-feet, usually has a surface-elevation between 4300 and 4400 feet above sea-level. Despite the relatively high altitude, air temperatures at the Dam have a mean annual value of 59°.6 F.

The temperature-curves shown on Figure 1 are probably typical for a large storage-reservoir, located in such a climatic environment. The only point which deserves special mention is the reduction in surface-temperature on March 28, 1935. The drop from 54° F, at a depth of five feet, to 50° at the surface, may be simply an error in observation or it may indicate that sudden reductions in overlying air-temperatures can cool the surface-water faster than it can sink and be replaced by warmer water. Similar surface-temperature conditions have been observed at Elephant Butte Reservoir on certain dates during other years of measurement.

It might also be interesting to point out that at no time during the year, even at the

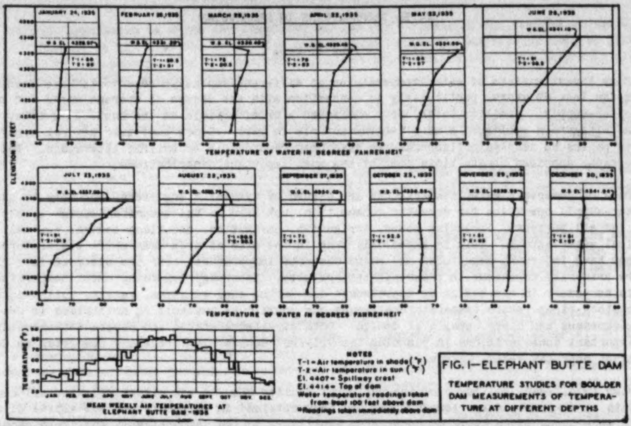

FIG. 1—ELEPHANT BUTTE DAM

TEMPERATURE STUDIES FOR BOULDER DAM MEASUREMENTS OF TEMPERATURE AT DIFFERENT DEPTHS

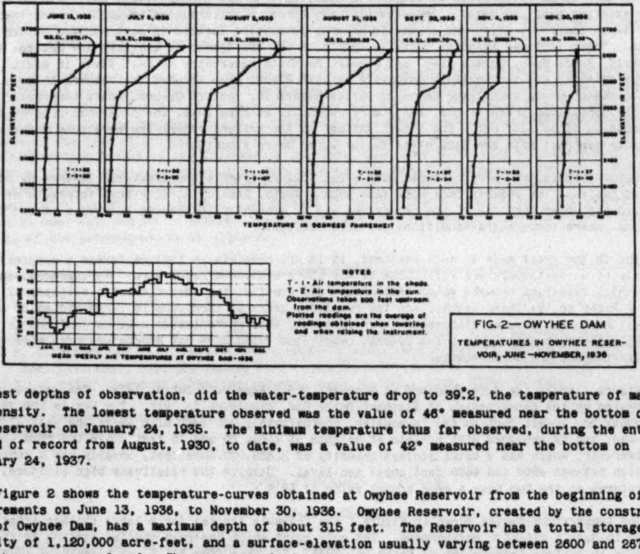

FIG. 2—OWYHEE DAM

TEMPERATURES IN OWYHEE RESERVOIR, JUNE—NOVEMBER, 1936

greatest depths of observation, did the water-temperature drop to 39°.2, the temperature of maximum density. The lowest temperature observed was the value of 46° measured near the bottom of the reservoir on January 24, 1935. The minimum temperature thus far observed, during the entire period of record from August, 1930, to date, was a value of 42° measured near the bottom on February 24, 1937.

Figure 2 shows the temperature-curves obtained at Owyhee Reservoir from the beginning of measurements on June 13, 1936, to November 30, 1936. Owyhee Reservoir, created by the construction of Owyhee Dam, has a maximum depth of about 315 feet. The Reservoir has a total storage-capacity of 1,120,000 acre-feet, and a surface-elevation usually varying between 2600 and 2670 feet above mean sea-level. The mean annual air-temperature is 46° Fahrenheit.

The principal point shown by the curves in Figure 2 is that seasonal temperature-variations in Owyhee Reservoir are practically confined to the upper 100 feet of depth. The total change at elevation 2550, from the warmest condition in the late summer to the coldest condition in the latter part of January, 1937, not shown on the diagrams, was only 10°; while the total change at the surface during the same period was 45°. Temperatures near the bottom of the Reservoir decreased to the value for maximum density about the end of February, 1937. It is interesting to note that measurements on December 30, 1936, showed a practically constant temperature throughout the entire 300 feet of depth, the observed values varying only from 42° at the bottom of the Reservoir to 43° at the surface.

Although Owyhee Reservoir was not filled to its maximum flow-line until April, 1936, water had been stored in the lower parts of the Lake from about the time the Dam was completed in 1932. Consequently, water-temperatures at the lower elevations, as shown on the curves in Figure 2, had had about four years in which to become adjusted to the varying temperatures of reservoir-inflow.

Figure 3 shows the temperature-curves obtained at Mead Lake from the beginning of measurements on June 10, 1936, to December 1, 1936. Mead Lake, created by the construction of Boulder Dam, has not yet been filled. When filled it will have a maximum depth of about 600 feet in the canyon just above the Dam. Some water was stored in the lower parts of the Reservoir during the latter part of the construction-period. The Dam was completed in 1935, and the diversion-tunnel outlet-gates, located at about the normal low-water surface of the River, were closed about May 1, 1936. Since that time, water has been released through the lower cylinder-gates, at a height of about 250 feet above the tunnel-gates. A second set of cylinder-gates, installed 150 feet above the lower set, may be used when the reservoir-surface rises to higher levels.

All future outflow for irrigation- and power-purposes will be released through either the lower or upper cylinder-gates. Consequently water-temperatures in the lower parts of the Lake, below the lower gates, may be expected to gradually decrease to about 40° F, approximately the temperature of maximum density. Measurements of the temperature of Colorado River water during the last seven years show that some flow at the temperature of maximum density will enter the Reservoir practically every winter. Such flows will naturally descend to the lower levels where they will accumulate until the surface of the maximum-density water rises to about the elevation of the lower gates. However, several years may be required for such temperature-transofmrations to take place, due to the relatively small quantities of 40° water entering the Reservoir. Furthermore, the temperature-transformations may be affected by the entrance of flood-flows, containing such heavy loads of suspended silt that their densities may exceed that of clear 40° water, even though their temperatures may be considerably higher. Therefore, it must be realized that the temperatures of Mead Lake water, observed thus far, merely show transitional conditions, not normal seasonal changes.

The curves in Figure 3 show that water-temperatures at the lake-surface increased from 76° on June 10 to 84° on August 1, then decreased to 63° on December 1. Temperatures at elevation 850 remained constant at 62° throughout the summer and fall. Temperatures at elevations below 850 increased gradually, probably due to the large quantities of relatively warm flood-water entering the Reservoir. Observations on September 1, October 1, November 3, and December 1, 1936, showed the presence of some unusually warm water near the bottom of the Reservoir, probably due mostly to increasesin density caused by the presence of suspended silt. The lowering of the upper limits of the warm water from October 1 to November 3 was probably due to the settling of the silt and the rising of the clear warm water to the upper part of the Reservoir as the density diminished.

Figure 4 shows the temperature-curves obtained at Mead Lake from January 6 to June 2, 1937. It is interesting to note the practically constant temperature at all elevations above 675 on January 6 and February 1, approximately 58° on the former date and approximately 53° on the latter. It is also interesting to note the gradually decreasing temperatures, between about elevations 675 and 900, from January 6 to April 2, probably due to the inflow of relatively cold river-water. The gradual increase in water-temperatures in the upper part of the Lake from February 1 to June 2 was probably a seasonal effect, accompanying the gradual increase in air-temperatures during the spring months. The presence of unusually warm water near the bottom of the Lake is shown by all curves.

Figure 5 shows the results of some special observations made on May 21, 1937, for the purpose of explaining the presence of unusually warm water near the lake-bed. Samples of the reservoir-water, for silt and chemical analyses, were taken at several depths below elevation 690.7. The samples showed the presence of silty water below about elevation 654, becoming very muddy at elevation 649.5 and having the color and consistency of thick chocolate below elevation 641. Analyses of the samples showed that the specific gravity of the water at laboratory-temperatures of 74° to 78° increased from 1.0014 for the sample from elevation 653.2 to 1.1731 for the sample from elevation 640.7,and 1.1787 for the sample from elevation 620.7. Likewise, the conductivity of the samples, which serve as a rough index of the total salt-content, expressed

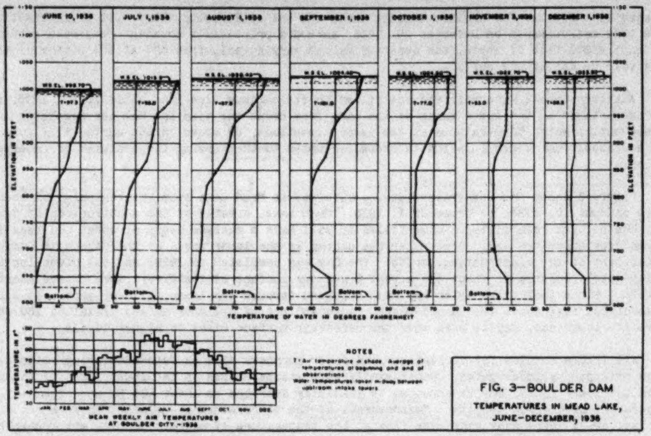

FIG. 3—BOULDER DAM

TEMPERATURES IN MEAD LAKE, JUNE-DECEMBER, 1936

in reciprocal ohms at laboratory-temperatures of 84° to 89°, increased from 0.00142 for the sample from elevation 653.2 to 0.00166 for the sample from elevation 640.7 and to 0.00161 for the sample from elevation 620.7. Thus it appears that the relatively high density of the warm water near the bottom of the Lake may be explained by the combined effects of a high salt-content and a heavy load of suspended silt, the latter probably being the more important.

The increased salinity and part of the increased temperatures near the bottom of the Lake are probably due to the presence of warm springs in the lake-bed. Construction Engineer Ralph Lowry, in a letter to Commissioner John C. Page dated May 29, 1937, said: "The known existence of warm springs in the Colorado River Canyon upstream from Boulder Dam, prior to construction, and the not uncommon temperature of 130° F in springs below Boulder Dam at the present time, may

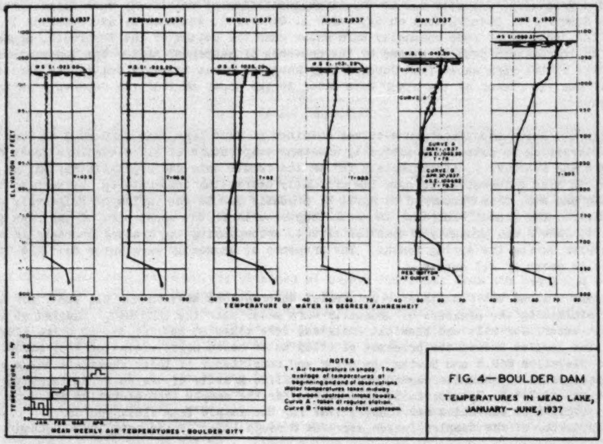

FIG. 4—BOULDER DAM

TEMPERATURES IN MEAD LAKE, JANUARY-JUNE, 1937

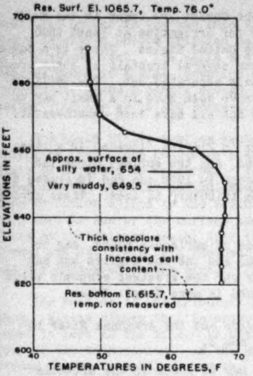

FIG. 5—TEMPERATURES NEAR BOTTOM OF MEAD LAKE, MAY 21, 1937

suggest one reason for the warm temperature near the bottom of Lake Mead at the Dam; and this heavy layer of colloidal clay in suspension may have an insulating effect tending to delay rapid temperature-diffusion upward from lower levels."

Although no chemical analyses of the water flowing from the warm springs are available at this time, salt deposits at the springs below the Dam show that the water must be highly alkaline. It will be interesting to make further analyses of the silt-, salt-, and temperature-conditions near the lake-bed as well as further studies of temperature-changes at different depths in the Reservoir later, when more data become available.

Technical investigations made in connection with the design of dams are conducted under the general direction of J. L. Savage, Chief Designing Engineer. All engineering and construction-activities are under the general supervision of R. F. Walter, Chief Engineer, with headquarters at Denver, Colorado; and all activities of the Bureau are under the supervision of John C. Page, Commissioner, with headquarters at Washington, D. C.

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RETURN-FLOW

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The term "return-flow" may be taken to mean any water after being once used that returns to a natural stream or any water beneath the surface of the ground that is in motion or under a pressure-head and will flow if the pressure is released. Return-flow may then be divided into four classes: (1) Definite underground streams flowing beneath the surface of the Earth; (2) sub-flow of surface-streams; (3) percolations tributary to water-courses; and (4) subterranean lakes or artesian belts.

Examples of definite underground streams are numerous in the United States especially in areas where extensive beds of limestone are prevalent. There are several instances where springs producing large amounts of water are in reality the outlets of underground rivers. One of the smaller ones is in the Muddy and Paranaget Valleys in Nevada above Boulder Dam. In this area with a rainfall of only about six inches a year and hundreds of miles from any apparent source, these streams come to the surface in the form of springs. Those in the Muddy Valley, located in an area about one-quarter mile square, produce a constant flow of 50 second-feet; in the Paranaget Valley, they produce about 25 second-feet from a smaller area. The temperature of this water is about 100° F when it comes out.

The lost-city ruins estimated to date back 1000 years before Christ are found in the Muddy Valley, and there are evidences that the inhabitants used water for irrigation at least 1500 years ago. This Valley probably produced the first sugar in the United States. There is a sugar-cane there that grows wild and when stung by some insect produces several crystals of sugar around the hole. The cane was gathered and beaten and the sugar-crystals separated out. The Smithsonian Institution has a pound or so of this sugar now. Attempts have been made in a small way to develop more water from this spring-area by drifts and tunnels, but all have been unsuccessful.

Other examples of underground rivers are the Silver Springs in Florida, located in a limestone-formation, which flow from 342 to 822 cubic feet per second, and the springs along the Snake River in Idaho, which flowed about 3900 cubic feet per second in 1902 and had increased to 5000 second-feet in 1918 due to increased irrigation in the area tributary to them. These springs occur in a basalt-area.

Perhaps the most noteworthy example of class No. 2, sub-flow of surface-streams, may be found in the valley of the South Platte in Colorado and Nebraska, and the Los Angeles and San Gabriel rivers in Southern California. Since class No. 2 has by far the greatest economic value as a source of irrigation-water in this area, it will be discussed in more detail later.

Examples of class No. 3 are the majority of our eastern rivers and the Arkansas River in this State, which might be considered an example of both Nos. 2 and 3.

An example of No. 4, artesian areas and underground lakes, may be found in the artesian

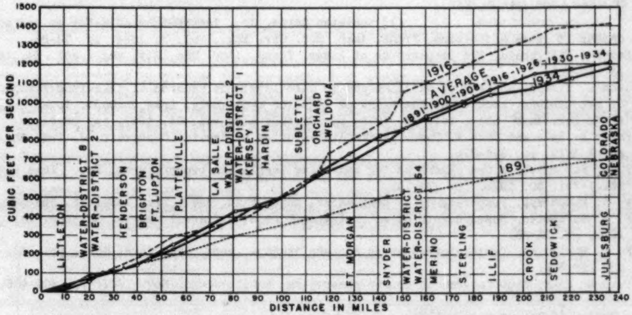


FIG. 1—GRAPH SHOWING THE MEASURED SEEPAGE RETURN FLOW TO THE S. PLATTE RIVER BETWEEN WATERTON AND JULESBURG [COMPRISING WATER-DISTRICTS 8, 2, 1, AND 64 FROM 1891 TO 1934 INCLUSIVE—FROM STATE ENGINEERS RECORDS]

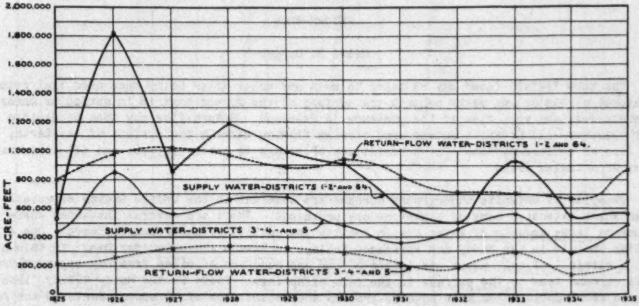


FIG. 2—TREND-CURVES SHOWING DIRECT FLOW SUPPLY AND RETURN-FLOW FROM SEEPAGE IN WATER-DISTRICTS 3, 4, 5, 1, 2, AND 64—FOR YEARS 1925-1935

belt near Denver in the San Luis Valley in southwestern Colorado, and Roswell Area in New Mexico. There is also a unique artesian belt around Las Vegas, Nevada, where one of the wells flows nearly ten second-feet. The wells are shallow in depth and the impervious strata overlying the water-bearing sands is a lime-formation deposited from downward percolating waters and sufficiently impervious to allow pressure enough to accumulate for the wells to flow, their source being much higher than the wells and perhaps a hundred or so miles distant.

The South Platte subflow mentioned before might well be considered a vast underground lake extending from above Denver to a point half way between Sterling and Julesburg, as far as the State of Colorado is concerned. The fact that there is very little return-flow coming into the River between Sterling and Julesburg might be accounted for by the fact that somewhere in that area an outlet exists to the south toward the Republican River in this so-called underground Lake. This Lake is fed by the surface and subflow of the streams entering the Platte starting with Plum Creek on the extreme south, then in their order going north, Bear Creek, Cherry Creek, Clear Creek, the St. Vrain, Big Thompson, Cache La Poudre, and several semi-dry streams coming in from the dry land-area on the east.

The subflow of the tributary streams is made up from the irrigation of lands adjacent to them. Wilson states that in order for underground waters to flow there must be a gradient of at least 15 feet to the mile. If that is true, this South Platte Lake would have arms extending up some of the tributaries. As the subflow from the tributaries pours into this Lake, the main stream becomes a spillway, and the excess is carried off as so-called return-waters.

It will be noted from the curves shown on Figure 1 that these return-waters have been increasing as the use of water has increased since irrigation began in 1860. The curves of supply and return-flow as drawn on Figure 2 show that the return-flow fluctuates with the supply. In some cases one or two years later and in some cases immediately. The reason for that could be explained, in a case of a year's lag, that time was required to raise the level of the Lake sufficiently to begin spilling while in the case of almost instantaneous relation between supply and runoff the Lake was just at the spilling stage.

Another stream that substantiates the underground-lake theory is the Gila in Arizona. A large portion of the Salt River Project is underlain with a porous water-bearing strata. The movement of this water is extremely slow, if at all, and large areas became water-logged. Drains in some instances proved effective, but the most efficient method tried was by pumping this water to the surface and using it over again for irrigation, where possible, or wasting it into natural channels.

A dam was constructed across the Gila some 35 miles below the mouth of Salt River. Cutoff-walls were put down in the hopes that the subflow would be intercepted and brought to the surface, but that did not happen, indicating that the flow was either very small or that it escaped somewhere else. The former is probably the fact, and that the major portion of the underground waters in the Gila Valley are stationary or in other words form underground lakes.

In the Salt River Valley from 150,000 to 200,000 acre-feet of water are pumped from this underground water and used for irrigation. This water was developed at a capitol cost of about $2900 per second-foot and with a pumping cost of about $0.40 per acre-foot.

The maximum of 1,300,000 acre-feet of underflow water available by gravity in the entire South Platte Valley is of inestimable value.

The Colorado-Big Thompson Project contemplates the bringing over of 310,000 acre-feet of water from the headwaters of the Colorado River into this South Platte Area. The City of Denver contemplates the bringing in of about 100,000 acre-feet from the Fraser and Williams rivers which are tributaries of the Colorado, and the Blue River-South Platte Project contemplates the bringing in of 375,000 acre-feet from the Blue also a tributary of the Colorado River.

It has been estimated, by making a comparison of the return-flow derived from the present South Platte supply and using the same percentages, that the return-flow from the 310,000 acre-feet in the Colorado-Big Thompson Project would amount to 214,000 acre-feet annually. When all the transmountain-diversions are completed there would be a return of approximately 550,000 acre-feet annually.

Just what the legal status of this return-water would be is an interesting question and the following is a brief outline of some of the laws in regard to it.

Legal aspects of return-flow--The legal status of return-flow has long been a debatable question and has been the subject of many lawsuits.

The first question of the ownership of return-flow or underground waters arose in England where the courts, rather strictly, held that the ownership of a tract of land involved everything above and below it, and if there were underground waters beneath the surface the owner could do as he pleased with it. The same idea prevailed in this country for a while.

When the use, however, of return-flow for irrigation and for domestic supplies became more general and its use by one party began to affect the use by other parties, the law began to change and free use was granted only when the rights of others were not affected.

In this proposed Colorado-Big Thompson Project the disposition of the return- or underflow-waters is of vital concern. As mentioned before, the probable return-flow for reuse lower on the river from the 310,000 acre-feet average brought over from the Colorado River has been estimated at 214,000 acre-feet and the following is a brief review of a few Colorado cases that might have a bearing on the legal standing of this water.

One case decided by the Colorado Supreme Court reported in 179 Pacific, page 873, entitled "McKelvey vs. North Sterling Irrigation District." It appears the outlet of the Reservoir crossed a natural draw across which the District had placed a dam. After irrigation had started, seepage developed below the dam and plaintiff sought to file on it and convey it to his lands by means of a canal. At the same time the defendant irrigation-district constructed a canal in such a manner as to divert the seepage or return-flow in question to its own lands. The plaintiff sought to stop them on the grounds that the water was wasted or abandoned as far as the defendant was concerned. The Supreme Court held that water lawfully in possession of an irrigation-district may, in absence of intent to abandon, be prevented from escaping, and water seeping through a dam may be recaptured by means of an irrigation-ditch and other persons have no right to appropriate it, and that said waters so escaping are not merged or mingled with any other waters, and that from the time said waters so began to escape it has been the intent of plaintiff to recapture said waters for irrigation of lands lying within its territorial limits.

In March 1920 the Colorado Supreme Court handed down another decision reported in 191 Pacific, page 135, in the case of the Rio Grande Reservoir and Ditch Company vs. The Wagon Wheel Gap Improvement Company. The Rio Grande Reservoir and Ditch Company had constructed Santa Maria Reservoir with a capacity of 43,565 acre-feet, started in 1896 and completed to full capacity in November 1913. After the Santa Maria Reservoir was constructed, seepage started from an adjacent hillside and the Santa Maria seepage-ditch was constructed, and it was planned to convey this water to the gates of a canal far down the stream and apply it to lands owned by the Company. The right is based upon the theory that the waters have been impounded in the Reservoir during the winter when direct irrigation is impossible. The Supreme Court decided the case as follows:

(1) An intention to abandon is not a forfeiture of rights to water appropriated. (One of the defendant's charges was that at one time the Reservoir Company had intended to abandon the entire project as evidenced by a letter written by an officer of the Company so stating.)
(2) Seepage water could not be appropriated to the detriment of prior appropriators.

Justices Burke, Dennison, and Garrigus dissented. The following is the dissenting opinion as written by Justice Garrigus:

"I lay down, as the first point in the discussion, that water which one has saved, developed, or produced, or which comes from an independent or extraneous source to the natural irrigation-flow of the stream and has been put into the river or a conduit by the producer or owner for the purpose of taking it out and using it lower down the stream for irrigation, belongs to the one who put it into the stream as against all priorities, or put in a way already expressed by this Court, one who by his own efforts increases the natural flow of a stream, either by saving or developing water, is entitled to its benefit to the extent of the increase as against all consumers regardless of priority. Citing Platte Valley vs. Buckers M and I Co. 25 Colorado, page 77, Ripley vs. Park Center L and W Co. 40 Colo. 129, and several others."

On March 6, 1922, the Colorado Supreme Court handed down another decision in the case of the Ft. Morgan Reservoir and Irrigation Company et al vs. State Engineer McCune reported in 206 Pacific, page 393. The Prewitt Reservoir belonging to plaintiff was constructed in the South Platte Valley about half way between the towns of Brush and Sterling. The reservoir-floor was in a very sandy area and the dam was constructed of sand with a concrete face. The Company, anticipating seepage, constructed a system of canals, measuring flumes, and other structures to collect and measure the seepage-water. A few weeks after the Reservoir began filling the seepage-ditches started flowing and finally reached a maximum of 60 cubic second-feet with an estimate of 35 second-feet escaping outside the canal. Since the Reservoir was constructed for supplemental purposes and the water stored was to be turned into the river and sold to purchasers lower down on the stream, or above by exchange, the Company attempted to dispose of this return-flow water they collected, basing their right to do so on the previous Supreme Court decisions and the State statutes. The Supreme Court held in this case, however, that "an appropriator of water is not entitled to seepage from its drainage and reservoir-ditch which will return to the stream."

Justice Burke dissented and his dissenting opinion certainly appeared to be in line with what the law was at that time and should be, the majority opinion being a reversal of the District Court's decision in the matter. He closed his opinion with these words: "I think the only authority for this reversal is dictum and the only principal departure."

You know we laugh as we read in ancient history some of the decisions of the Oracle of Delphi. When Croesus inquired of the Oracle if his contemplated war against Cyrus would be successful, she said, "It will mean the destruction of a great nation." He went to war and found out the great nation was his own. He had, however, no comeback on the Oracle as she did not state what nation. A lot of our Court decisions are like the Oracle when it comes to really deciding an issue.

The investigation of some cases reviewed by the United States Supreme Court in regard to return-flow reveals that they follow very closely the dissenting opinion of Judge Garrigus in the Rio Grande case. Some of these decisions are: United States vs. Ramsey et al District Court of Nebraska, North Platte Division, Dec. 20, 1918, found in Federal Reporter, vol. 254. In this case the Interstate Canal diverting water from the North Platte River in Wyoming and serving lands in Nebraska crossed a draw known as Sheep Creek. After the project was in operation for some time, seepage developed in the Creek and the defendant Company constructed a lateral and attempted to appropriate the water. The United States Reclamation Service brought suit to enjoin them and the United States Supreme Court decided as follows: Under revised statutes, Nebraska 1913Ss. 3426-27, and in view of the general statutory scheme for the acquisition of water-rights, held the defendant water-company, which had the right to appropriate water from the Platte River, was not entitled to appropriate seepage-water escaping from the Interstate Canal constructed by the United States under the Reclamation law, with the consent of the State of Nebraska, which water had been impounded by the United States.

Another case that has a bearing on return-flow is in the case United States vs. Haga found in Federal Reporter 276, pages 41 to 43, August 10, 1921. The following is the decision as written by United States District Court Judge Dietrich:

"One who by the expenditure of money and labor diverts appropriable water from the stream and thus makes it available for fruitful purposes, is entitled to its exclusive control so long as he is able and willing to apply it to beneficial uses and such rights extend to what is commonly known as wastage from surface-runoff and deep percolation necessarily incident to practical irrigation.

"It is not necessary to keep in continuous possession so long as he does not abandon it. It is not necessary to confine it on his own land or in an artificial conduit.

"He may conduct it through natural channels and may even co-mingle or suffer it to co-mingle with other water. The rights of the appropriator are not affected that the water has once been used."

The final case investigated in regard to return-flow was Ide vs. The United States, reported in 68 Law Ed. October term 1923, pages 263-265. This case had to do with waters in Bitter Creek on the Shoshone Project in Wyoming. Bitter Creek passed through the Shoshone Project and run water from melting snow and when it rained, but had no live water during the irrigation-season. Irrigation on the project started in 1908 and by 1910 the Creek had a constant flow of return-water. The Government sought to enlarge and straighten the Creek through the lands of the plaintiff and to make use of the water. The Court held the Government had a right to enlarge the Creek and in regard to the use of return-water handed down the following decision by Justice Van Devanter:

(6) "The right to water appropriated by the Government under an irrigation-project does not cease when it has been once used for irrigation but the water is subject to second use in accomplishment of the Reclamation for which the appropriation was first made.

"The United States, in conferring water-rights upon purchasers of land under a reclamation-project, does not surrender its rights to utilize the water again after it has served its purpose for the purchaser."

The bringing into the South Platte Drainage of the 310,000 acre-feet from the Grand Lake Project, the 105,000 acre-feet of the City of Denver from the Fraser and Williams, and the 375,000 acre-feet proposed from the Blue and Williams, or a total of 780,000 acre-feet of direct water and the estimated amount of underflow or return-water for reuse of 555,000 acre-feet will undoubtedly work wonders in Northeastern Colorado. In addition to the 1,335,000 acre-feet of new water available for irrigation and domestic use, over 1,500,000,000 kw-hours of cheap electrical energy can be generated.

It would be of vast interest to the development of eastern Colorado and western Kansas if some Government agency, preferably the United States Geological Survey, could be allocated sufficient funds to make a survey to determine the location and approximate quantities of underflow waters. There is an abundance of excellent land on which this water could be used and with cheap power available areas where the pump lift exceeds even 150 feet could be profitably farmed.

U. S. Bureau of Reclamation,
Denver, Colorado

VALLEY CONSUMPTIVE USE

E. B. Debler

(Published with the approval of the Commissioner, U. S. Bureau of Reclamation)

Duty of Water as a term to define use of water, is as old as irrigation in the United States and has been carried into many of our water-laws. Confusion in its use is commonplace. Implying efficiency, the term was used in law to define limitations in diversions or deliveries specified in acres per second-foot of water or acre-feet per acre annually. The amounts specified were intended to be the amounts actually required, with good husbandry.

Almost from the start of irrigation, observers called attention to the appearance of return-flow. The same type of flow in the non-irrigated regions is generally termed "base-flow." Both represent return to the stream of unused ground-waters.

Increasing return-flow, and particularly that from large areas reaching long distances inland with enormous ground-water reserves built up from irrigation-diversions, led to the commonplace remark that stream-flow was increased by return-flow and that irrigation made no inroads on stream-flow but merely equated it. More thorough students appreciated the fallacy of these claims, which smacked of perpetual motion, since the depletion of our streams by irrigation could not be overlooked.

They also appreciated the need for information on the actual loss of water through irrigation. Some experimenters carried out extensive measurements on duty of water with a view to ascertaining the minimum requirements and the relative efficiency of heavier applications. Others selected soils of exceptional water-retaining qualities, to eliminate, so far as practicable, percolation-losses to the underlying ground-water. Investigators with laboratory leanings developed and experimented with various types of lysimeters, many of which were of a size that might be expected to reflect field-conditions for specific crops or other vegetation. Related to these investigations and at times concurrent therewith, were the experiments to ascertain plant-requirements independent of soil-evaporation, determined by retarding or preventing such losses for a limited time by stopping access of the air to soil surrounding the plants.

The term "consumptive use" was coined to fit the need for a term to define the loss of water incident to irrigation. It was legally recognized for the first time in the Colorado River Compact, formulated in 1921, to govern uses of that stream, allocations being designated "beneficial consumptive use." It does not carry as significantly the idea of efficiency but expresses more clearly a measure of the permanent depletion of the available water-supply. While the term is not yet in common use and is often misunderstood, it has been in use by the Bureau of Reclamation for fully 20 years.

Consumptive use was defined in the Report of the Duty of Water Committee of the Irrigation-Division of the American Society of Civil Engineers, presented July 14, 1927 (Trans. Amer. Soc. Civ. Eng., vol. 94, 1930, p. 1351), as: "Consumptive use in a basic sense is here defined as the quantity of water, in acre-feet per cropped acre per year, absorbed by the crop and transpired or used directly in the building of plant-tissue, together with that evaporated from the crop-producing soil." Since it is impracticable to confine water-loss to crop-producing area, the term is not ordinarily used in the sense in which that Committee defined. The more common use is more properly defined as "valley consumptive use."

"Valley consumptive use" is the difference between valley inflow, consisting of the runoff of streams entering the valley, either on the surface or as underflow, together with precipitation, and outflow from the valley, in the form of water either in surface-streams or an underflow, with suitable adjustment for changes in ground-water storage. It represents the total water-loss from the valley-area by evaporation and transpiration, except for water contributed by dew, frost, or fog, together with the small amount retained by the plant-structure. Applied to many western valleys where agriculture is dependent upon irrigation and the irrigated area is the economic unit, it may well be stated in terms of acre-feet per year per irrigated acre.

As an illustration of a valley-consumptive-use study, the Mesilla Valley of the Rio Grande Federal Reclamation Project has been chosen and a study covering the ten-year period 1927 to 1936, made. It is about 55 miles long and three miles wide, with a valley-floor area of about 109,000 acres, 94,000 acres of which are irrigable and has an irrigated area of about 74,000 acres. The average annual precipitation is slightly less than nine inches, most of which occurs during the summer. The temperature-range in the period studied was between 6° and 104°.

In the Valley are the Leasburg and Mesilla divisions of the Rio Grande Project of the Bureau of Reclamation. Water is mainly supplied from Elephant Butte Reservoir which controls the flow of the Rio Grande. Other inflow to the Valley consists only of the storm-runoff of arroyos usually dry. A very small amount of underflow may come from the adjacent mesas. Diversions are made at the Leasburg Dam by the Leasburg Canal and at the Mesilla Dam by the East Side and West Side canals. Adequate drainage is furnished by 12 well-developed open-drain systems averaging ten feet in depth. The Mesilla Valley was chosen for illustration because of its hydrographic suitability, because of its low rainfall, because of the relatively little unmeasured inflow, because it offers a long period of adequate records since reaching substantially complete irrigation-development, and because, unlike most western valleys, it has suffered little, if any, shortage of water during recent dry years.

Records of stream-inflow were taken from project-records appearing mostly in the annual project-histories. They consist of the measured runoff of the Rio Grande at Leasburg, including the Leasburg Canal, and arroyo-inflow estimated by project-engineers from a comparison of daily hydrographs of the river-stations corrected for time-lag, and precipitation on the valley-floor as indicated by local stations. The outflow-record is that of runoff of the Rio Grande at El Paso, which in the earlier years, was published by the United States Geological Survey, and in recent years appears in the annual reports by the International Boundary Commission. Ground-water changes were based on average changes in water-levels of from 53 to 83 test-wells applied to an area of 104,000 acres with a yield coefficient of 30 per cent. Underflow into and out of the Valley was neglected. Estimates of arroyo-inflow and depletion of ground-water as used in the analysis, because of small amount of basic data, are probably not very accurate. In most years, however, these quantities represent less than 1/2 per cent of the total supply. Table 1, following, gives the valley-consumptive-use analysis for Mesilla Valley by years. Table 2 gives the mean monthly distribution of valley consumptive use for the same period.

Table 1--Valley consumptive use in the Mesilla Valley, New Mexico and Texas-Rio Grande Project of the United States Bureau of Reclamation
(Unit is 1000 acre-feet unless otherwise stated)

Year (1)	Rio Grande at Leasburg (2)	Arroyo inflow (3)	Precipitation (4)	Ground-water correction (5)	Rio Grande near El Paso (6)	Total Valley consumption (7)	Irrigated area in acres (8)	Valley consumptive use in acre-feet per irrigated acre (9)	Valley consumptive use in acre-feet per acre of valley area (10)
1927	873.4	3.2	82.1	-2.5	619.6	336.6	73314	4.59	3.09
1928	912.3	3.2	75.0	-0.5	623.6	366.4	76057	4.82	3.36
1929	768.4	0.5	79.9	+10.7	552.6	306.9	76722	4.00	2.81
1930	789.1	1.5	62.4	+2.2	532.4	322.8	76373	4.23	2.96
1931	738.3	2.7	114.3	+1.6	515.6	341.3	76722	4.44	3.13
1932	814.1	2.0	80.9	-4.9	567.3	324.8	76709	4.24	2.98
1933	824.0	0.0	40.8	+1.1	609.2	256.7	77061	3.33	2.35
1934	768.1	0.4	43.7	-12.5	508.4	291.3	68605	4.15	2.67
1935	632.2	1.2	109.7	+3.1	459.9	286.3	62175	4.61	2.63
1936	693.2	2.0	82.2	-6.2	473.7	297.5	74813	3.98	2.73
Mean	781.3	1.7	77.1	-0.8	546.2	313.1	73855	4.24	2.87

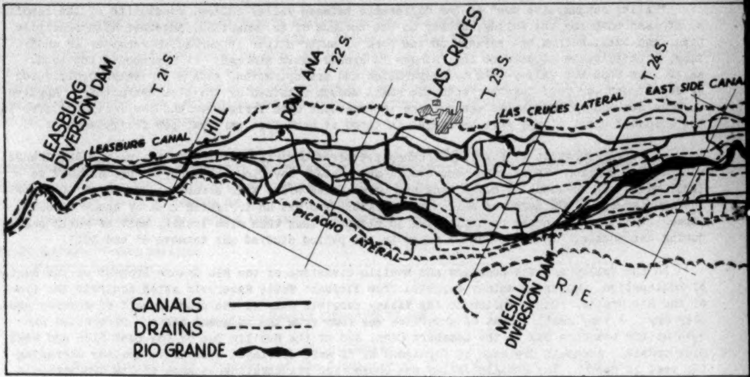


Table 2--Mean monthly distribution of Valley consumptive use Mesilla Valley-New Mexico and Texas-Rio Grande Project of the United States Bureau of Reclamation

(Unit is 1000 acre-feet unless otherwise shown)

Month (1)	Rio Grande at Leasburg (2)	Arroyo inflow (3)	Precipitation (4)	Ground-water correction (5)	Rio Grande near El Paso (6)	Total Valley consumption (7)	Irrigated area in acres (8)	Valley consumptive use in acre-feet per irrigated acre (9)	Valley consumptive use in acre-feet per acre of valley area (10)
Jan.	6.4	0.0	2.8	+4.7	10.6	3.3	.....	0.04	0.03
Feb.	25.6	0.0	3.6	-1.3	19.4	8.5	.....	0.12	0.08
Mar.	60.1	0.0	2.1	-9.1	36.8	16.2	.....	0.22	0.15
Apr.	103.2	0.1	1.6	-17.2	59.7	28.0	.....	0.38	0.26
May	93.2	0.0	4.8	-6.5	62.0	29.5	.....	0.40	0.27
June	109.9	0.0	4.8	-5.7	66.8	42.2	.....	0.57	0.38
July	124.7	0.5	14.8	-3.7	79.6	56.7	.....	0.77	0.52
Aug.	127.4	0.9	18.8	-0.7	90.3	56.1	.....	0.76	0.51
Sept.	80.6	0.2	8.5	+6.6	60.2	35.7	.....	0.48	0.33
Oct.	23.5	0.0	5.8	+16.6	26.5	19.4	.....	0.26	0.18
Nov.	14.8	0.0	4.8	+9.7	18.5	10.7	.....	0.15	0.10
Dec.	11.9	0.0	4.7	+6.0	15.8	6.8	.....	0.09	0.06
Total	781.3	1.7	77.1	-0.8	546.2	313.1	73855	4.24	2.87

The irrigated area of the Mesilla Valley represents about 68 per cent of the total valley-area. The balance consists of town-areas, waste-land, or water-surface. While these areas are not intentionally irrigated, they consume much water derived from farm-wastes and seepage from canals, the River, or irrigated lands. Along the water-courses, trees, brush, grass, and swamp-growth consume water to an extent varying from small rates to rates exceeding evaporation free-water surfaces. Evaporation from the valley-water surfaces is probably greater than from lake- or reservoir-surfaces because of narrow width permitting exceptional air-contacts, riffles, wetting of sand-surfaces, etc. The average evaporation-rate from the Weather Bureau Class A pan at the Agricultural College is approximately 93 inches. It is probable that evaporation from the River, canals, and drains may amount to as much as six feet per year.

Data are not available to permit segregation of waste-areas into water-using categories. It is, however, not unlikely that consumptive use for the waste-areas averages as high as on irrigated areas.

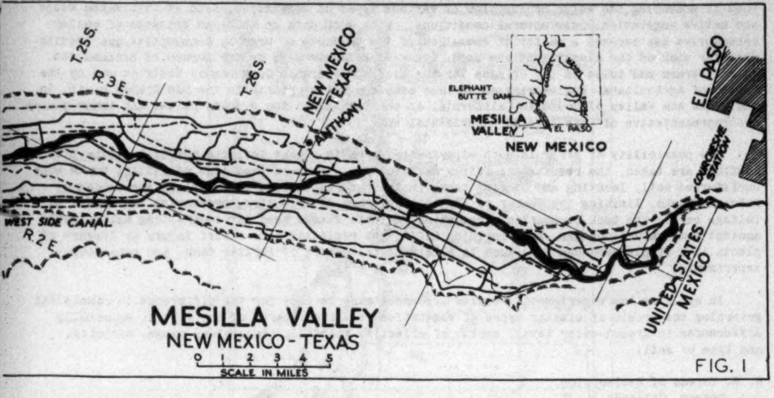


FIG. 1

In non-irrigated regions, consumptive use of water by waste-lands is not particularly detrimental to use by cropped lands. In irrigated regions where water is artificially applied, irrigation is an investment and losses to non-productive uses represent a loss on that investment.

In general, our irrigation-development is limited by water rather than land. The extent of the ultimate development will then be governed by consumptive use per irrigated acre. In many districts, conversion of waste-areas to cropped lands is possible without any increase in the valley consumptive use. Such projects as the Middle Rio Grande Conservancy District have been constructed on this premise. Complete elimination of waste-areas is not always possible or even desirable. Reclamation of some areas by drainage or by removal of unprofitable vegetation is economically infeasible. Growth of willows and cottonwoods is sometimes beneficial as the roots of these trees have an inherent value in preventing erosion along streams, strengthening fills, and furnishing needed shade. With growing values for water, other means of bank-protection can be adopted.

A lowering of ground-water levels not only increases the soil available to the crop-producing plant with increased production, but lessens soil-evaporation and restricts the growth of useless plants. The southern San Joaquin Valley areas served by ground-water pumping are models of this type of development and their prevailing consumptive use of 2 to 2.5 acre-feet per acre is a tribute to their economy in the use of water. In most localities, water has not yet reached a value justifying similar developments.

Plant-selection offers possibilities. Our most common forage-plant, alfalfa, is well known as a heavy water-user. Strains of this plant can be developed to produce equal crops with less water.

From the standpoint purely of water-conservation, the goal is the application to useful plants of the minimum water required for most efficient crop-production. Water should be applied only in amounts that can be held in the soils without escape to ground-waters. An immense benefit of such an operation would be the elimination of pollution of streams by return-flows, which are consistently higher in salts than the stream-flow. Repeated rediversion of waters raises the salt content of stream-flows to points requiring heavy irrigation to avoid soil-water concentration beyond plant-tolerance limits, and finally makes the entire flow unfit for further use. Reduction in return-flow results in retaining more salts nearer their origin and facilitates further downstream development. There appears to be a decided limitation with such a practice in that limited water-penetration in any area is likely to lead to the formation of hardpans, which, if impervious, grow upward and eventually preclude crop-production.

Where it is desired to estimate the changes in valley consumptive use upon a change in the type of use such as an irrigation-development, it is necessary to base estimates upon experimental determination of the consumptive-use requirements of the types of vegetative cover and soil or water-surfaces involved. In recent years, many tank-experiments have been made for the purpose of measuring the water-consumption of various types of vegetation, both of cultivated crops and native vegetation under natural conditions. With such data at hand, an estimate of valley consumptive use becomes a matter of summation of the products of area by consumptive-use requirement for each of the classifications used. Tank-experiments made by the Bureau of Reclamation on salt-grass and tules at Los Griegos for the Middle Rio Grande Conservancy District and by the Bureau of Agricultural Engineering on various crop and native plants in the Rio Grande Basin, in the Santa Ana Valley of Southern California, in the Sacramento-San Joaquin Delta, and other places are representative of this type of experimental work.

The possibility of error in such experimental work is almost infinite but if adequate precautions are taken, the results are fairly satisfactory. Present technique of filling tanks with undisturbed soil, locating and burying tanks in the natural habitat of the plant surrounded by natural growth, limiting the number of plants to average distribution, preventing the spread of foliage beyond the tank-boundaries, insulating Mariotte flasks used for controlling water-levels against temperature-changes, and providing sufficient replication to offset injury or disease of plants in a single tank has done much to eliminate the errors of earlier tank- and potometer-experiments.

In applying the experimental results allowance must be made for the difference in conditions governing the growth of similar types of vegetation in various parts of the valley, especially differences in ground-water level, amount of effective rainfall, temperature-range, humidity, and type of soil.

U. S. Bureau of Reclamation,
Denver, Colorado

GROUND-WATER IN UTAH

George H. Taylor

(Published with the approval of the Director, U. S. Geological Survey)

In common with many of the arid and semiarid States, the prosperity of Utah probably is more dependent upon the amount of water available than upon any other natural resource. Although only about four per cent of the State is irrigated, a shortage of water for irrigation becomes a major calamity. A large part of the water-supply for the State is derived from surface-streams, but a most valuable supplement to this supply is the water available from underground sources. Ground-water is used extensively for domestic, stock-watering, and industrial purposes as well as for irrigation. The primary source of the municipal water-supply for Salt Lake City is from streams entering the Jordan River Valley from the western slope of the Wasatch Mountains. However, since the drought-year of 1931, a supplementary municipal supply has been obtained from ground-water, and, among the 17 wells developed by the City during the extreme drought of 1934, one--yielding about ten cubic feet per second, or 4500 gallons a minute--is probably the largest in the State. Ogden, the second largest city in Utah, with a population of about 40,000, obtains the major part of its municipal water-supply from a group of artesian wells in Ogden Valley about 12 miles east of the City. A considerable part of the water-supply for the City of Brigham is obtained from wells. Springs constitute the source of most of the water-supply for Logan, Provo, and many smaller towns and localities in the State. In nearly every developed area of the State ground-water is used for some purpose, and in some areas the water-supply is obtained almost entirely from wells.

Utah lies in four of the major ground-water provinces of the United States (Fig. 1). The Columbia Plateau lava province, in the extreme northwestern part of the State, is relatively unimportant in Utah, principally because of its small extent. The Northern Rocky Mountain province, in the northeastern part of the State, is also relatively unimportant from the standpoint of ground-water supplies in the State. However, a large part of the surface-water supplies of the State is obtained from the area included in that province. The Montana-Arizona Plateau province extends over about the southeastern half of the State. Ground-water is found in this area under conditions varying from place to place. Often the supplies are not of satisfactory quality, and, on the whole, they are not plentiful. However, along the central Sevier River Valley and the Sanpete Valley, which are adjacent to and drain into the Southwestern Bolson province, relatively plentiful supplies of ground-water of good quality are found. The Southwestern Bolson province occupies most of the western part of Utah and contains the bed of the ancient Lake Bonneville, of which Great Salt Lake, Utah Lake, and Sevier Lake are the principal remnants. It is in the stream- and lake-deposits of the Lake Bonneville Basin that the largest and most valuable ground-water supplies of Utah are now found. The best and most plentiful supplies exist along the eastern margin of the basin, adjacent to the western slope of the Wasatch

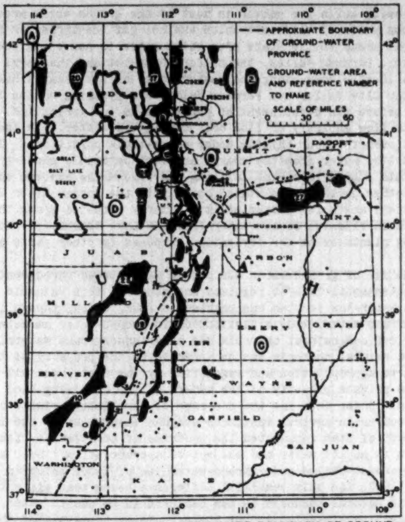

114°
113°
112°
111°
110°
109°
42°
41°
40°
39°
38°
37°
APPROXIMATE BOUNDARY OF GROUND-WATER PROVINCE
GROUND-WATER AREA AND REFERENCE NUMBER TO NAME
SCALE OF MILES
0
30
60
A
B
C
D
BOX ELDER
CACHE
RICH
SUMMIT
DAGGETT
GREAT SALT LAKE DESERT
TOOELE
UTAH
UINTA
DUCHESNE
JUAB
CARBON
MILLARD
SANPETE
EMERY
GRAND
SEVIER
BEAVER
WAYNE
PIUTE
GARFIELD
IRON
SAN JUAN
WASHINGTON
KANE
20
17
28
2
27
11
10
21
12

FIG. 1—SKETCH SHOWING APPROXIMATE BOUNDARY OF GROUND-WATER PROVINCES AND KNOWN GROUND-WATER AREAS IN UTAH

REFERENCE-LETTER AND NAME OF GROUND-WATER PROVINCE

A-Columbia Plateau lava province
B-Northern Rocky Mountain province
C-Montana-Arizona Plateau province
D-Southwestern Bolson province

REFERENCE-NUMBER AND NAME OF GROUND-WATER AREA

1-Ashley Valley
2-Bear Lake Valley
3-Beaver Valley
4-Blue Springs Valley
5-Cache Valley
6-Cedar City Valley
7-Central Sevier Valley
8-Chicken Creek Valley
9-East Shore Area
10-Escalante Valley
11-Fremont Valley
12-Goshen Valley
13-Grass Valley
14-Grouse Creek Valley
15-Jordan River Valley
16-Juab Valley
17-Malad and Lower Bear River Valley
18-Ogden Valley
19-Pahvant Valley
20-Park Valley
21-Parowan Valley
22-Provo Valley
23-Rush Valley
24-Sanpete Valley
25-Sevier Desert
26-Tooele Valley
27-Uinta Basin
28-Upper Bear River Valley
29-Upper Sevier Valleys
30-Utah Lake Valley
31-Cedar Valley

Mountains. Here the sediments are predominantly coarse--especially near the mouths of the steep canyons which drain the mountains to the east--and were well sorted by the littoral currents of the ancient lake. Hence these deposits are exceedingly permeable and are among the most productive aquifers in the State. The ground-water generally becomes less satisfactory, both as to quantity and quality, toward the central and western parts of the Bonneville Basin, where the sediments are chiefly fine sand, silt, and clay. Contained within the Southwestern Bolson province are many intermontane valleys in which considerable ground-water has been developed, most commonly from the alluvial fans that lie at the mouths of streams entering these valleys.

The known ground-water areas in Utah are sketched on Figure 1. The boundaries of most of these areas are indefinite and it is probable that some of the areas shown as individual units are actually continuous with adjacent areas. Of these areas, the ones bordering on the west slopes of the Wasatch Mountains, from the southern end of Utah Lake to the Utah-Idaho boundary in Cache Valley, probably supply the greatest part of the ground-water recovered in the State.

Recovery of ground-water occurs through flowing and pumped artesian wells and pumped non-artesian wells. Flowing wells are common in most of the ground-water areas. Some flowing wells also exist in various parts of the State which are not yet identified or outlined as ground-water areas. The principal areas in the State from which water is now being pumped for irrigation are: The Cedar City Valley, Parowan Valley, the Milford District and the Beryl District in Escalante Valley, and about a 15-mile zone along the western base of the Wasatch Range south of Brigham. Of these areas, Cedar City Valley and Parowan Valley are artesian basins in which there were many flowing wells before the development of pumped wells for irrigation. Now most of these wells have ceased to flow entirely or flow only during the winter. In the Escalante Valley ground-water is believed to occur chiefly under water-table conditions. The pumping district south of Brigham derives water from the coarse and very permeable shore-gravels of the ancient Lake Bonneville. This pumping district is along and beyond the eastern edge of the area of artesian flow. In other parts of the State, notably in the Jordan River Valley, Utah Lake Valley, and Cache Valley, there are a few pumped wells similarly situated along the eastern edge of areas of artesian flow, which likewise obtain water from the Lake Bonneville shore-gravels. Isolated ground-water pumping plants exist for irrigation-purposes in other parts of the State.

Even though the use of ground-water has become wide-spread throughout the State, no adequate legislation was enacted until 1935 to regulate and conserve this valuable natural resource. The first comprehensive water-law in Utah was enacted in 1903, which, though it satisfactorily regulated the use of surface-water, made a distinction in ground-water as between subterranean waters flowing in known or defined natural channels and other underground waters. Ground-water flowing in known and defined natural channels was declared to be the property of the public, subject to existing rights and to appropriation and regulation by the State, but all other ground-water was considered to be the private property of the owners of the overlying land and not subject to statutory regulation. Under this law the doctrine of correlative rights or reasonable use was upheld by the Utah courts in several instances and was thought to be the law until January 1935, when the Supreme Court of Utah repudiated the doctrine of correlative rights and held that water in an artesian basin is public water and subject to appropriation. Soon after this the Utah Legislature enacted the so-called underground-water law of 1935, which is practically the same as the water-law of 1903, the only essential difference being that all water of the State rather than water flowing in natural channels is now declared to be public water, subject to existing rights. Therefore, all public water in the State is to be appropriated and regulated through the State Engineer. The active application of the new law during the past two years has resulted in the curbing of much waste from flowing wells and a control over unrestricted drilling and use of pumped and flowing wells. Previous waste and unrestricted development had, along with several successive years of drought, caused an alarming lowering of the ground-water levels in most parts of the State.

Adequate and just regulation of the use of ground-water requires a knowledge of the level at which the ground-water lies, the fluctuations of and causes of the fluctuations of the ground-water level, the amount and relationship of the recharge to and the discharge from each ground-water basin, and many other factors governing the supply. As a preliminary step toward obtaining this knowledge, the State Engineer, in cooperation with the United States Geological Survey, began an investigation of the State's ground-water on July 1, 1935. During the past two years a comprehensive program has been established whereby records of the fluctuations of the ground-water level in the major ground-water areas of the State are being obtained. Records of the upward or downward trend of the ground-water level during successive years probably indicate best the relationship between the recharge to and discharge from the ground-water area--a factor of utmost importance in the administration of the ground-waters.

Some detailed records of ground-water levels prior to 1935 are available, particularly in the Jordan River and Ogden valleys, where investigations were carried on since 1931 by the United States Geological Survey, and in the areas near Cedar City, Milford, and Fillmore, where measurements were made through the initiative of the Utah State Agricultural Experiment Station.

The fluctuations of the water-level in wells in these areas since 1931 or 1932 are shown by Figure 2. Discussion of these hydrographs and the causes of the fluctuations will be limited to a few of the most pertinent facts. Well (A-6-1)12aal is located a short distance below the upper limits of the Ogden Valley artesian area, from which the artificial discharge is mainly through a group of about 50 wells used by the City of Ogden for a municipal supply. Prior to 1937 the hydrograph of this Well shows the highest yearly water-level occurring during May or June and the lowest during February or March. The low-water level during September or October of each year is an artificial condition caused by heavy summer withdrawals from the artesian basin. During November and December the recovery from the effects of the summer withdrawals gives a double amplitude to the curve of the yearly cycle. This type of hydrograph is also characteristic of wells in some parts of the Jordan River Valley. The rise of the water-level after the extreme

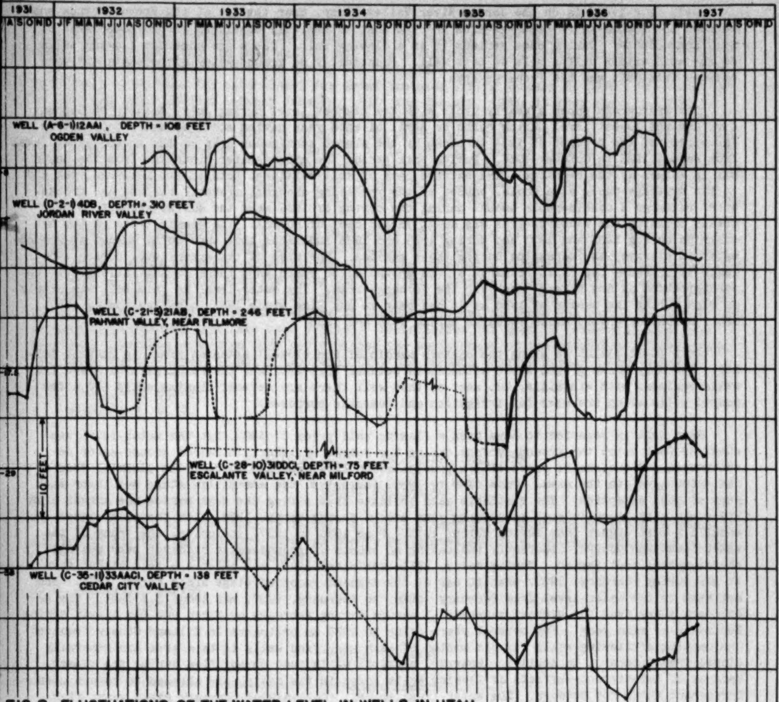


FIG. 2—FLUCTUATIONS OF THE WATER-LEVEL IN WELLS IN UTAH.

low level during October of the drought-year of 1934 illustrates the rapid recharge of the ground-water basin when there is available sufficient precipitation and surface-runoff or irrigation over the recharge-area. That the water-level rose to nearly the same level during each of the years 1933, 1934, 1935, and 1936 is significant inasmuch as this indicates that the high level during each of these years may be about the normal level of the ground-water in this well when the artesian reservoir is approximately full. During the past two years a unique situation has been created in Ogden Valley by the building of the Pine View Dam on the Ogden River, the outlet of the valley. The reservoir created by this dam covers a large part of the artesian reservoir and also covers the artesian wells of the City of Ogden with about 30 feet of water. The outlet of these wells was lowered several feet and a gravity-conduit laid below the bottom of the reservoir and through the dam where it joins the City's gravity-conduit. These operations occurred during the fall of 1936 and, to some extent, disturbed ground-water conditions that might have existed under normal operation. To the writer's knowledge, the loading of an artesian reservoir with a surface-reservoir has not heretofore occurred, and the resulting effects upon the artesian reservoir are yet problematical. The rise of the water-level in well (A-6-1)12aa1 during March, April, and May, 1937, was at least partly caused by the partial filling of the surface-reservoir as the two events occurred almost simultaneously. The rise may be a pressure-effect resulting from the surface-load imposed on the artesian confining layer, or an effect resulting from the stoppage of leaks through the confining layer, or an effect of the retardation and possible reversal of the tendency of the artesian water to move upward through the confining layer, or a combination of these effects.

Well (D-2-1)4db is on the Jordan River Valley floor, near the toe of the Provo Terrace and between the ground-water recharge-area and the most extensively developed ground-water area of Salt Lake County. During some periods it is a flowing well. There are numerous flowing wells to the west within half a mile of this Well. Practically no ground-water withdrawals are made between this Well and the recharge-area.

The hydrograph shows a yearly cycle with the highest level during July, August, or September, and the lowest level during March or April of each year having about normal precipitation. The effect of the drought of 1934 is shown by the almost continuous drop of the ground-water level from August 1933 to October 1934. During this period the ground-water discharge from the basin was in excess of the recharge. The extreme lack of soil-moisture, both in the recharge-area and in the drainage-basin as a whole, caused by the preceding drought, probably reduced the ground-water recharge a considerable amount during the spring of 1935 when the surface-runoff in the creeks crossing the recharge-area was about 75 per cent of normal. The upward trend of the hydrograph during 1932 and 1933 and during 1935 and 1936 indicates that that total amount of ground-water in storage was increasing during those periods. The rise of the water-level during 1936 again illustrates the rapid recharge of the ground-water basin when there is available sufficient precipitation on and stream-flow over the recharge-area. The water-level in this well was nearly as high during the summer of 1936 as it had been at any time since 1931, notwithstanding the small amount of ground-water recharge during 1934 and 1935.

Well (C-21-5)21ab is along the eastern margin of the Flowell artesian area in Pahvant Valley. The only known ground-water withdrawals between this Well and the recharge-area are a few wells equipped with windmills, but west of this Well there are several flowing wells and a few pumped wells which are used for irrigation and domestic purposes.

This Well is reported to have been a flowing well prior to 1927, but the water-level was about 23 feet below the ground-surface during the summer of 1936. Increased ground-water developments and successive years of low precipitation have combined to cause an alarming drop of the water-level in the area. From 1929 to 1935, inclusive, the annual low stage was lower each year without exception. The available data indicate that during the same period the annual high stage was also lower in each succeeding year except during March, 1934, when the water-level was about 1.2 feet higher than during March, 1933. From 1935 to 1937, inclusive, the trend of the water-level was upward, apparently indicating an excess of ground-water recharge over the discharge during that period. During March, 1931, the water-level was about 4.5 feet higher than it was during February, 1937, when it was at its highest recorded stage since March, 1931. The net gain in the water-level from February, 1936, to February, 1937, was about 3.5 feet. The hydrograph shows that the highest water-level occurs during February or March and the lowest during September of each year. For several years prior to 1935 an ordinance in Millard County required the capping of flowing wells for six months of each year, and wells in this area are generally closed from October 1 to April 1. However, marginal wells that do not flow during the summer, because of interference-effects of flowing wells lower in the basin, are allowed to remain open throughout March and October. The water-level in Well (C-21-5)21ab commonly rises about five feet within a few days after October 1 and rises still more after the marginal wells are closed on November 1. These rises are pressure-effects resulting from the cessation of ground-water withdrawals from wells in the area and do not indicate recharge of the ground-water reservoir. In the spring a slight decline of the static level during March appears to result from the opening of marginal wells, and a much greater decline follows the opening of the larger flowing wells during April. These declines are again pressure-effects representing the interference with the water-level in the observation-well caused by withdrawing water from other wells in the area. The effects are most clearly shown on the hydrograph after September, 1935, at which time a recording-gage was placed on the Well.

Well (C-28-10)31ddc1 is in Beaver County in the northern part of Escalante Valley. A district of intensive pumping, commonly called the Milford Area, occupies a zone one to three miles to the north and west of this Well, which is near the margin of the heaviest developments.

The records of ground-water levels in this district are too few and irregular to permit close interpretation, but they show that there has been a considerable decline during the 10 or 15 years since the time the pumping of ground-water for irrigation began. Although the hydrograph of Well (C-28-10)31ddc1 is incomplete, it shows a net decline of the water-level between 1932 and 1935 and an upward trend of the water-level from September, 1936, to May, 1937, inclusive. The available measurements of the ground-water level in the area show that the water-level has dropped 10 feet or more since 1921. However, in the spring of 1937 the water-level in this Well was about as high as in the spring of 1932.

Well (C-35-11)33aacl is located along the eastern margin of a district of intensive pumping of ground-water for irrigation a few miles north and west of Cedar City. The available measurements of the water-level in this Well do not show a distinct annual cycle, although the rise due to spring-recharge and the decline during the irrigation-season are definitely indicated. The hydrograph shows that the water-level was about the same during January of 1932, 1933, and 1934; it declined about 10 feet between January, 1934, and January, 1935; it rose about 1.4 feet between January, 1935, and January, 1936; and it declined about 3.3 feet between January, 1936, and January, 1937. During 1932 the trend of the water-level was upward, but since 1932 the general trend has been downward. A net decline of 12 feet has occurred between January, 1933, and January, 1937. These figures indicate a serious excess of ground-water withdrawal from the area. During the summer of 1936 the pumping lift in Well (C-35-11)31aacl was about 86 feet. During January, 1937, the static water-level in the same well was about 67 feet below the ground-surface.

Lowering of ground-water levels in most parts of the State has been caused both by the recent successive years of drought and by increasing withdrawals of ground-water. In some years considerable waste of ground-water has occurred from improperly constructed wells and from wells that were allowed to flow when the water was not used. However, these conditions are now being improved as fast as practicable. The ground-water levels in most parts of the State have risen during the past two years, partly because of abundant natural recharge and partly because of the conservation-measures that have been applied. Nevertheless, it must be remembered that this generally favorable condition does not diminish the seriousness of the situation in areas that have been overdeveloped, of which the Cedar City and Parowan valleys appear to be examples.

U. S. Geological Survey,
Washington, D. C.

FLOODS OF 1935 IN THE REPUBLICAN RIVER

Robert Follansbee

[The content of this paper is largely given in Water-Supply Paper 796-B "Flood on Republican and Kansas rivers, May and June 1935" by Robert Follansbee and J. B. Spiegel, published in 1937 by the United States Geological Survey.]

U. S. Geological Survey,
Denver, Colorado

FLOODS IN TEXAS

Robert Lowry

(Published with the approval of the Commissioner, U. S. Bureau of Reclamation)

Floods in Texas, with their ever-increasing list of damages and loss of life, have within recent years become one of the major problems confronting the State. During the eight years since 1929 losses due to floods in Texas have conservatively been estimated by the United States Weather Bureau at more than $50,000,000.

While the damages from floods are undoubtedly increasing, the runoff-records do not indicate that floods are necessarily increasing either in magnitude or frequency. The greater damages are due primarily to man's encroachment upon the natural flood-ways. In fact, if historical evidence is to be considered, a number of well-established high-water marks of earlier floods indicate higher stages at many points than have been reached since runoff-records began.

Floods in Texas are the result of excessive rains. It follows that since rainfall is not distributed uniformly as to either total depth or intensity, all parts of the State are not subject to floods to the same degree. The greatest annual amounts of precipitation occur near the eastern border of the State, where more than 50 inches of rain is to be expected each year. In contrast to this, there is less than 10 inches in the extreme western part of the State in a normal year. The variation between these extremes is relatively uniform, the precipitation decreasing with rise in elevation.

Annual precipitation is ordinarily no criterion upon which to base floods. However, it is a fairly definite limit to the amount of precipitation which may be expected to occur in one storm, for only rarely does the precipitation of a single storm exceed the normal annual rain-

Table 1--Recorded rainfalls of 10 inches or more in 24 consecutive hours

Rain-fall	Station	Date	Rain-fall	Station	Date
24.00	Hearne	June 28, 1899	11.60	Kerrville	July 14 and 15, 1900
24.00	Broome	Sept. 16 and 17, 1936	11.40	Austin	Oct. 15, 1870
23.11	Taylor	Sept. 9 and 10, 1921	11.40	Austwell	July 22, 1919
20.60	Montell	June 29, 1913	11.30	Hillsboro	Sept. 26, 1936
20.40	Water Valley	Sept. 16 and 17, 1936	11.30	Ricardo	June 21, 1924
19.03	Austin	Sept. 9 and 10, 1921	11.30	Halletsville	July 1, 1936
18.25	Christoval	Sept. 16, 1936	11.05	Rockland	May 28, 1929
18.00	Ft. Clark	June 15, 1899	11.00	Marble Falls	Sept. 10, 1921
16.02	Hill's Ranch	Sept. 10, 1921	11.00	Turnersville	June 29, 1899
15.71	Matagorda	May 1, 1911	11.00	Turnersville	June 30, 1899
15.60	Eagle Pass	June 29, 1936	11.00	Turnersville	July 1, 1899
15.60	Mercedes	Sept. 4 and 5, 1933	11.00	Waco	Oct. 2, 1913
14.28	Galveston	July 13 and 14, 1900	10.92	Matagorda	Oct. 24, 1914
14.22	Nacogdoches	June 28, 1902	10.89	Gainesville	July 19, 1919
14.21	Kaufman	Aug. 23, 1908	10.75	Midland	Apr. 19, 1888
14.10	Galveston	Oct. 7 and 8, 1901	10.60	Marshall	Apr. 26, 1921
13.85	Conroe	May 30, 1924	10.60	San Augustine	Aug. 18, 1915
13.54	Beaumont	May 18 and 19, 1923	10.50	Alice	Sept. 15, 1919
13.53	Uvalde	July 2, 1932	10.50	Arthur City	May 12, 1920
13.30	Bonham	July 3, 1903	10.44	Brownsville	Sept. 6 and 7, 1935
13.08	Brackettville	Oct. 1 and 2, 1881	10.43	Beeville	July 3, 1903
13.03	San Marcos	Oct. 2, 1913	10.35	Port Arthur	May 28, 1915
13.00	Georgetown	Sept. 10, 1921	10.32	Brownsville	Sept. 21, 1886
12.90	Kaufman	Sept. 27, 1936	10.27	Galveston	June 12, 1925
12.67	San Benito	Sept. 5, 1933	10.10	Matagorda	June 22, 1921
12.45	Cameron	Sept. 10, 1921	10.07	Gainesville	July 2, 1903
12.43	Brackettville	May 28, 1880	10.05	Orange	May 28, 1915
12.35	Sinton	Apr. 28, 1930	10.05	Sabinal	Apr. 20 and 21, 1936
12.22	Port Lavaca	Aug. 10, 1903	10.02	Brenham	Oct. 3, 1902
12.19	Galveston	Oct. 22, 1913	10.00	Austin	Apr. 23, 1915
12.00	Freeport	July 22, 1933	10.00	Brazoria	Sept. 8, 1900
12.00	George West	Sept. 15, 1919	10.00	Brazos	May 8, 1922
12.00	Harlingen	Sept. 4 and 5, 1933	10.00	Brownsville	Sept. 4 and 5, 1933
12.00	Tennyson	Sept. 17, 1936	10.00	Edna	June 22, 1921
11.96	Cuero	July 23, 1919	10.00	Fairfield	Sept. 4, 1932
11.91	Brownsville	Sept. 22, 1886	10.00	San Marcos	Oct. 19, 1909
11.80	Mexia	Sept. 4, 1932	10.00	San Marcos	Dec. 4, 1913
11.75	San Angelo	Sept. 15, 1936			

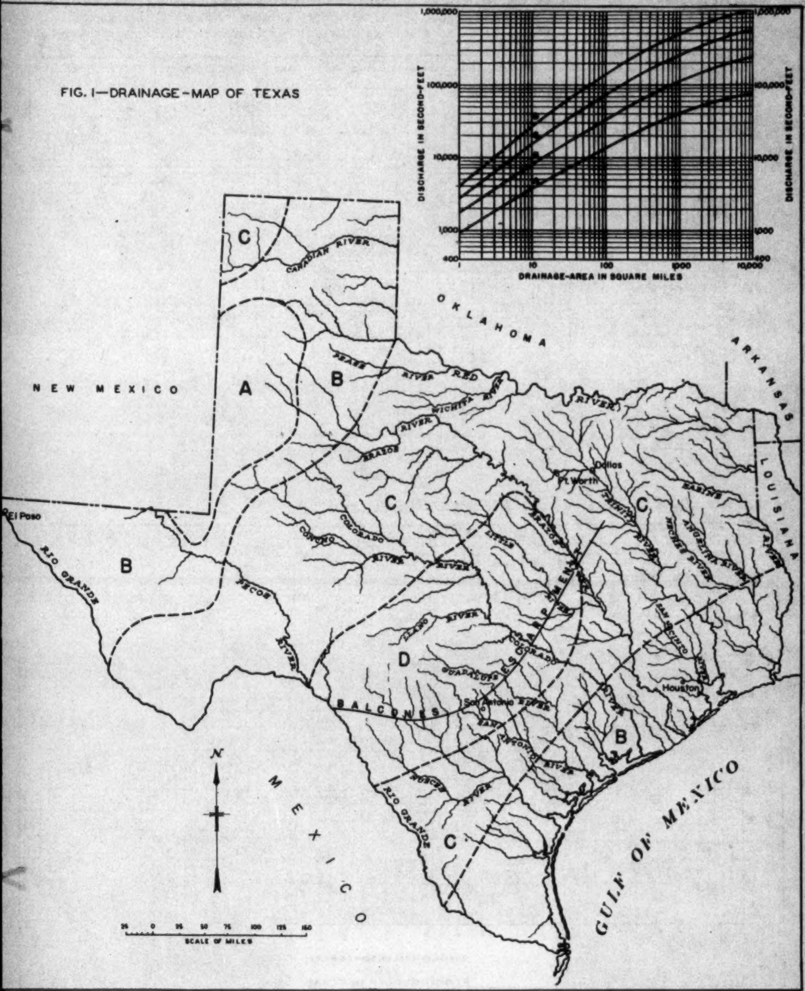
fall in that area. Therefore, the same depth of rainfall from single storms cannot be as great where the annual amount is less than 10 inches, as where 40 or 50 inches is expected.

The largest single factor in producing floods is the quantity of storm-rainfall which occurs at an excessive rate. "Excessive rate" is in itself a variable, determined from local conditions of topography, soil-structure, and vegetal cover. These factors control the absorptive power of the watershed. No appreciable runoff will occur until the precipitation-rate has exceeded the absorptive power. In passing from a humid to a semiarid region the rate of absorption will probably not be uniform.

Dynamic cooling of the atmosphere results in the condensation of moisture therein which is then precipitated as rain. This is the cause of practically all flood-producing storms in this country. The dynamic cooling, and consequent rainfall, is brought about by an ascensional movement of the air, caused usually by one of three or a combination of three ways. The upward movement of the air may be caused by heat with circulation nearly vertical, creating such conditions as are encountered in the tropics. Augmented evaporation caused by the heat results in increased precipitation, as there is little lateral movement of the air to carry away local evaporation.

Dynamic cooling is also produced by topographic features of the land, such as hills and mountains. The horizontal air-currents are forced upward by the mountains in their path, being cooled as they ascend. Condensation then takes place, resulting in precipitation. Evaporation from the region to windward forms a large part of the source of such rainfall.

A third way by which dynamic cooling is affected, and the way that produces most of the precipitation throughout the United States is cyclonic circulation. Cyclonic circulation is due to high and low pressure-areas on the Earth's surface which produce air-movements toward the low-pressure areas from all directions, circulation being in a spiral counter-clockwise direction in the Northern Hemisphere. With this type of circulation, cold air coming down from the northern


DISCHARGE IN SECOND-FEET
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400
DRAINAGE-AREA IN SQUARE MILES
1
10
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A
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D
NEW MEXICO
OKLAHOMA
ARKANSAS
LOUISIANA
MEXICO
GULF OF MEXICO
CANADIAN RIVER
PEASE RIVER
RED RIVER
WICHITA RIVER
BRAZOS RIVER
CONCHO
COLORADO RIVER
LITTLE
PECOS RIVER
RIO GRANDE
LLANO RIVER
GUADALUPE
SAN ANTONIO RIVER
NUECES RIVER
TRINITY RIVER
NECHES RIVER
ANGELINA RIVER
SABINE RIVER
SAN JACINTO RIVER
BALCONES ESCARPMENT
El Paso
Dallas
Ft Worth
San Antonio
Houston
N
SCALE OF MILES
25 0 25 50 75 100 125 150

FIG. 1—DRAINAGE-MAP OF TEXAS

latitudes mingles with the warm air from the south. The latter being lighter is forced to rise and in so doing is cooled. If the air from the south is laden with moisture, the cooling effect, both of the north winds and the dynamic action, will be such as to cause precipitation.

Two general classes of cyclonic movement are recognized, extra-tropical cyclones and tropical cyclones or hurricanes. The extra-tropical cyclonic movements are climatic disturbances of varying intensity which pass over the United States with more or less regularity in a general easterly course. The West Indian hurricanes are cyclonic in character and originate in the Gulf

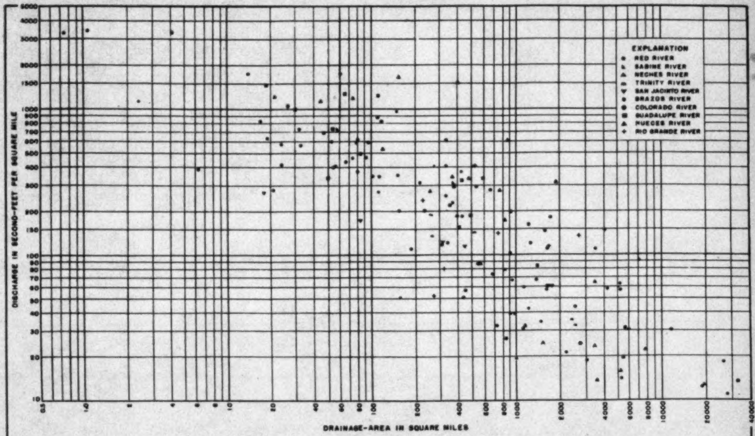

FIG. 2—
MAXIMUM EXPERIENCED RUNOFF IN TEXAS

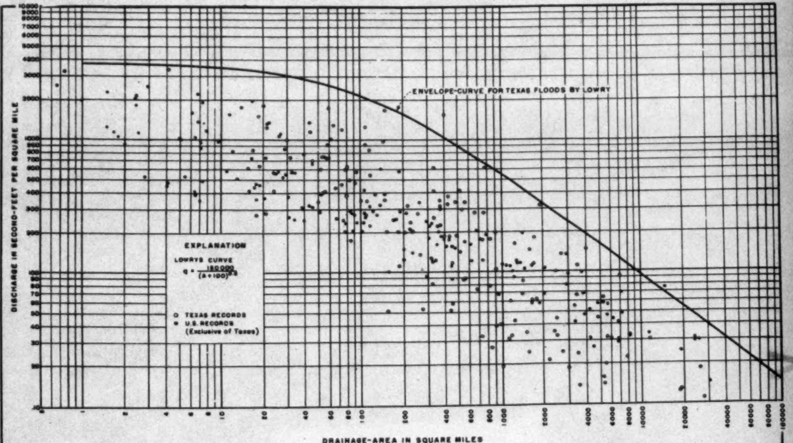

FIG. 3—
FLOOD-RUNOFF IN TEXAS

Table 2--Major floods in Texas

No.	Stream and location	Drainage-area, square miles	Year	Discharge, sec-feet per square mile
1	Red Bank Creek, near San Angelo	0.76	1936	3280
2	Seven Mile Draw, Ames	2.4	1936	2140
3	Bunton Branch, near Kyle	4.1	1936	3370
4	Little Barton Creek, near Bee Cave	6.3	1929	389
5	Dry Creek, near San Angelo	14.0	1936	1760
6	West Fork of Grape Creek, near Carlsbad	17.0	1936	836
7	Little White Oak Bayou, Sylvester St. Bridge, Houston	18.1	1935	273
8	Alazan Creek, near San Antonio (near mouth)	18.7	1921	1497
9	East Fork of Terrett Draw, near Ft. McKavett	19.0	1936	637
10	West Fork of Terrett Draw, near Ft. McKavett	21.0	1936	280
11	Atascosa River, near Benton City	21.3	1924	1220
12	Golston Draw, near Ft. McKavett	24.0	1936	417
13	Walnut Creek, near Marble Falls	24.0	1936	567
14	Olmos Creek, at Dam Site, San Antonio	26.4	1921	1061
15	O'Neil Creek, near Leesville	30.0	1936	1000
16	East Fork of Grape Creek, near Carlsbad	32.0	1936	724
17	East Fork of Terrett Draw, near Ft. McKavett	33.0	1936	567
18	Sabinal River, near Vanderpool	45.7	1932	1140
19	San Pedro Creek, near Apache Creek, San Antonio	46.5	1921	698
20	Bear Creek, near Hunt	50.3	1932	342
21	Grape Creek, near Carlsbad	53.0	1936	600
22	North Fork of Medina River, at Lima	54.0	1932	744
23	Onion Creek, Dripping Springs	54.8	1929	400
24	Miller Creek, Johnson City	56.3	1929	407
25	Flat Fork Creek, near Center	58.0	1933	728
26	East Fork of James River, Old Knoxville	60.8	1932	1730
27	South Fork of Guadalupe River, near Hunt	65.3	1932	1290
28	Hamilton Creek, near Marble Falls	67.0	1936	435
29	Brushy Creek, Round Rock	74.7	1921	462
30	East Fork of Frio River, near Leaky	75.0	1932	1190
31	Childress Creek, near China Springs	79.0	1936	595
32	Pecan Creek, near San Angelo	81.0	1936	377
33	West Fork of Copperas Creek, near Roosevelt	81.0	1936	622
34	San Antonio River, below San Pedro Creek	85.0	1921	499
35	Whiteoak Bayou, at MKT bridge, Houston	85.3	1935	173
36	Blanco River, near Blanco	92.2	1929	472
37	Sandies Creek, near Dewitt	95.0	1936	572
38	Terrett Draw, near Ft. McKavett	103.0	1936	348
39	North Fork of Guadalupe River, near Hunt	110.0	1932	982
40	Johnson Creek, near Ingram	111.0	1932	1240
41	Sulphur Creek, near Lampasas	112.0	1936	271
42	Barton Creek, near Riley	114.0	1929	346
43	Copperas Creek, near Roosevelt	118	1936	838
44	Dry Frio River, near Reagan Wells	120	1935	539
45	Salado Creek, near Salado	148	1921	966
46	Onion Creek, near Buda	151	1929	352
47	Seco Creek, near D'Hanis	153	1935	1660
48	Bear Creek, near Junction	155	1936	201
49	Gonzales Creek, at Breckenridge	157	1924	50.7
50	Middle Valley Prong of San Saba River, near Ft. McKavett	188	1936	111
51	Paint Creek, near Telegraph	218	1935	318
52	Pinto Creek, near Del Rio	229	1932	239
53	Medina River, near Medina	235	1932	203
54	Sabinal River, at Sabinal	258	1932	278
55	Mountain Creek, near Grand Prairie	267	1928	134
56	Limpia Creek, near Fort Davis	272	1932	52.2
57	Buffalo Bayou at G. H. and S. A. R. R. Bridge, Houston	319	1935	125
58	Toyah Creek, near Balmorhea	324	1932	80.6
59	Nortn Valley Prong of San Saba River, near Ft. McKavett	328	1936	118

Table 2--*Major floods in Texas*--Continued

No.	Stream and location	Drainage-area, square miles	Year	Discharge, sec-feet per square mile
60	James River, near Mason	336	1932	256
61	Guadalupe River, near Ingram	336	1932	613
62	Onion Creek, near Delvalle	337	1921	409
63	Sandy Creek, near Marble Falls	344	1936	121
64	Plum Creek, near Luling	356	1936	220
65	Frio River, at Rio Frio	371	1932	345
66	Aquilla Creek, near Gholson	372	1936	227
67	Tenaha Creek, near Joaquin	374	1933	313
68	Blanco River, at Wimberley	378	1929	299
69	Hondo River, near Hondo	400	1932	187
70	West Fork of Nueces River, near Brackettville	402	1935	1520
71	Medina River, near Pipe Creek	412	1932	155
72	Blanco River, near San Marcos	429	1929	324
73	San Gabriel River, near Georgetown	431	1921	371
74	S. Concho River, at Christoval	434	1936	185
75	North Llano River, near Roosevelt	443	1936	51.0
76	Buffalo Bayou, at Lockwood St. Bridge, Houston	458	1935	115
77	Elm Creek, at Ballinger	458	1935	57.0
78	Frio River, at Concan	485	1932	334
79	Sandies Creek, near Westhoff	493	1936	188
80	Sycamore Creek, near Del Rio	524	1935	410
81	South Llano River, near Telegraph	540	1935	296
82	Brady Creek, at Brady	554	1930	87.4
83	Guadalupe River, at Kerrville	570	1932	334
84	Jim Ned Creek, near Brownwood	668	1932	280
85	San Saba River, near Ft. McKavett	688	1936	73.7
86	Spring Creek, near Tankersly	734	1936	32.6
87	Dry Devils River, near mouth	748	1932	172
88	Nueces River, at Laguna	764	1935	279
89	East Fork of Trinity, near Rockwall	831	1935	78.0
90	Frio River, near Uvalde	840	1932	176
91	Cypress Creek, near Jefferson	848	1930	26.7
92	West Fork of Nueces River, near Cline	880	1935	609
93	Cedar Creek, near Trinidad	910	1936	38.9
94	North Llano River, near Junction	914	1936	104
95	Guadalupe River, near Comfort	916	1932	199
96	Navasota River, near Easterly	949	1900	66.8
97	North Bosque, near Clifton	974	1935	39.3
98	West Fork of Trinity River, at Bridgeport	1010	1915	19.3
99	Middle Concno River, near Tankersly	1128	1936	31.0
100	San Saba River, at Menard	1151	1936	59.6
101	Atascosa River, at Whitsett	1171	1935	32.7
102	Lampasas River, at Youngsport	1242	1936	42.8
103	San Marcos River, at Ottine	1249	1929	162
104	Pedernales River, near Spicewood	1294	1929	120
105	North Concho River, near Carlsbad	1406	1936	67.3
106	Guadalupe River, near Spring Branch	1432	1932	84.5
107	Double Mountain Fork of Brazos River, near Aspermont	1510	1926	34.4
108	Angelina River, near Lufkin	1575	1932	24.3
109	Pecan Bayou, near Brownwood	1614	1932	146
110	Bosque River, at Lake Waco Dam	1660	1936	57.5
111	Guadalupe River, at New Braunfels	1666	1935	60.6
112	North Concho River, at San Angelo	1675	1936	110
113	Lozier Creek, near Langtry	1728	1935	114
114	Llano River, near Junction	1762	1935	181
115	San Jacinto River, near Humble	1811	1929	61.3
116	Nueces River, near Uvalde	1930	1935	319
117	San Antonio River, near Falls City	2067	1936	7.9
118	Clear Fork of Brazos River, at Nugent	2220	1932	21.2

Table 2--Major floods in Texas--Concluded

No.	Stream and location	Drainage-area, square miles	Year	Discharge, sec-feet per square mile
119	West Fork of Trinity River, at Fort Worth	2431	1922	35.0
120	South Concho River, at San Angelo	2535	1936	43.8
121	Elm Fork of Trinity River, near Carrollton	2535	1935	32.4
122	Devils River, near Juno	2733	1932	135
123	Sulphur River, near Darden	2754	1930	24.4
124	San Saba River, at San Saba	3046	1922	18.7
125	Angelina River, at Horger	3435	1915	23.9
126	Frio River, near Derby	3493	1932	65.8
127	Llano River, near Castell	3514	1935	110
128	Neches River, near Rockland	3539	1935	13.7
129	Devils River, near Del Rio	4060	1932	147
130	Concho River, near San Angelo	4217	1936	54.5
131	Little River, near Little River	5240	1921	63.2
132	Concho River, near Paint Rock	5257	1936	57.3
133	Nueces River, at Cotulla	5260	1935	15.7
134	Colorado River, at Ballinger	5340	1936	14.1
135	Frio River, at Callihan	5491	1932	19.8
136	Guadalupe River, at Victoria	5676	1936	31.5
137	Trinity River, at Dallas	6001	1908	30.7
138	Little River, near Cameron	7034	1921	92.0
139	Neches River, at Evadale	7908	1884	22.1
140	Sabine River, near Bon Wier	8323	1933	7.57
141	Brazos River, near Mineral Wells	13860	1930	6.90
142	Trinity River, at Riverside	15500	1908	5.59
143	Nueces River, near Three Rivers	15600	1919	5.45
144	Brazos River, near Glen Rose	15600	1935	6.26
145	Colorado River, near San Saba	18800	1900	12.4
146	Brazos River, at Waco	19260	1936	12.8
147	Colorado River, at Austin	26350	1935	18.3
148	Colorado River, at Smithville	27850	1935	11.0
149	Colorado River, at Eagle Lake	29140	1935	6.07
150	Brazos River, near Bryan	29190	1935	4.76
151	Red River, near Denison	32840	1935	6.91
152	Brazos River, at Richmond	34810	1929	3.16

of Mexico close to the Equator from whence they travel slowly in a west or northwesterly direction. When and wherever these warm southeasterly winds are met by a mass of cooler air from the northwest intense precipitation is usually the result.

Texas, bordering on the western end of the Gulf of Mexico, is adjacent to an abundant supply of moisture. As the warm, moisture-laden winds move inland from the Gulf, they are gradually raised with the topography until the equilibrium between temperature and pressure can no longer be maintained, and precipitation results.

During such disturbances, it is not unusual for enormous volumes of rainfall to occur over a wide area. A list of the recorded rainfalls of 10 inches or more that have occurred within 24 consecutive hours at various Texas stations is shown in Table 1. In most cases these rainfalls have resulted from storms of tropical origin.

According to runoff-characteristics, the State may be divided into four zones. These distinctive areas have been superimposed on a drainage-map of Texas, as shown on Figure 1. The boundaries of these zones were determined as accurately as possible from physiographical features, and then checked against records of maximum runoff that have been observed in each.

The lowest unit-runoff in Texas occurs in the area designated as Zone A, situated on the High Plains, and separated from the lower stream-channels by an escarpment known locally as the "Cap-rock." The many shallow depressions in this area catch practically all of the surface-runoff, and hold it for evaporation or deep seepage, with the result that little escapes to the streams below.

Table 3--Major floods in United States exclusive of Texas

No.	Stream and location	Drainage-area, square miles	Year	Discharge, sec-feet per square mile
1	Mann's Run, Creswell Station, Pa.	0.67	1914	2540
2	Skyrocket Creek, Ouray, Colo.	1.00	1923	2000
3	Mad Creek, LeRay, N. Y.	1.50	1916	2300
4	Magpie Gulch, near Golden, Colo.	1.50	1923	1270
5	Brook at Bradford, N. Y.	1.68	1935	1150
6	Unnamed Arroya, near Pueblo, Colo.	1.80	1921	1060
7	Cherryvale Creek, at Cherryvale, Kan.	2.00	....	930
8	Soft Water Creek, near Cold Spring, N. Y.	2.34	1935	2030
9	Missouri Canyon at Mouth, Colo.	2.40	1923	1810
10	Harrisburg Hollow, near Hickory Hill, N. Y.	2.49	1935	1130
11	Elizabeth River at Irvington, N. J.	2.79	1932	523
12	Glenn Creek, near Townsend, N. Y.	2.91	1935	2520
13	North Canyon, Centerville, Utah	4.00	1923	450
14	Horse Creek, Depauville, N. Y.	4.10	1935	476
15	Glenn Brook, Hammondsport, N. Y.	4.96	1935	1010
16	Hall's Gulch, Boise, Idaho	5.00	1913	1000
17	Steele Brook, near Delhi, N. Y.	5.40	1935	528
18	Hogan's Gulch, Eden, Colo.	6.10	1904	1580
19	Roger's Creek, Azusa, Calif.	6.40	1926	406
20	Strang's Brook, near Smithville Flats, N. Y.	6.41	1935	1040
21	Honey Creek, New Carlisle, Ohio	6.70	1920	2200
22	Blue Ribbon, Pueblo, Colo.	6.70	1921	1360
23	Stephens Creek, near Carson, N. Y.	7.04	1935	952
24	Templeton Gap, near Colo. Springs, Colo.	7.10	1922	862
25	Cameron Arroya, near Pueblo, Colo.	7.30	1921	1900
26	Catlin Mill Creek, Odessa, N. Y.	7.33	1935	491
27	Osteen Arroya, Pueblo, Colo.	7.80	1921	1160
28	Saw Kill, near Shady, N. Y.	9.50	1935	966
29	Willet Creek at Marathon, N. Y.	11.0	1935	585
30	Trumansburg at Trumansburg, N. Y.	11.5	1935	1550
31	Saw Kill, near Bearsville, N. Y.	12.1	1935	825
32	Sand Coulee, near DuBois, Wyo.	13.0	1934	515
33	North Arroya, near Pueblo, Colo.	15.6	1921	619
34	Big Creek, near North Hornell, N. Y.	16.5	1935	721
35	Peabody River, near Glen House, N. Y.	17.4	1927	421
36	Five Mile Creek, Enfield, N. Y.	18.0	1935	466
37	Little Red Creek, Circle, Wyo.	18.0	1934	358
38	Bayou Gulch, Franktown, Colo.	19.0	1922	460
39	Willow Creek, near Heppner, Oregon	20.0	1903	1800(?)
40	Creek, Burdette, N. Y.	20.6	1935	365
41	Merrill Creek, near upper Lisle, N. Y.	20.8	1935	726
42	Glenn Creek, Watkins Glenn, N. Y.	21.3	1935	1310
43	Cane Creek, N. C.	22.0	1901	1340
44	Pinal Creek, near Globe, Ariz.	25.0	1904	560
45	Boggs Creek, near Pueblo, Colo.	26.0	1921	582
46	Morgan Creek, near Chapel Hill, N. C.	27.0	1924	1110
47	Ellis River above Wildcat Brook, Jackson, N. H.	28.0	1927	529
48	Burro Canyon, Madrid, Colo.	29.0	1925	852
49	Dudley Creek, near Lisle, N. Y.	29.6	1935	547
50	Arroya Seco, Pasadena, Calif.	30.5	1914	374
51	Moosa Canyon, near Bonsalt, Calif.	31.0	1916	269
52	Crow Creek, near Cheyenne, Wyo.	34.0	1924	251
53	Pecks Creek, near Pueblo, Colo.	34.4	1921	564
54	North Branch of Hoosic River at N. Adams, Mass.	38.9	1927	314
55	Peabody River, near Gorham, N. H.	40.0	1927	248
56	Granada Creek, near Granada, Colo.	40.0	1935	775
57	Sweetwater Creek, near Descanso, Calif.	43.7	1927	326
58	Elkhorn Creek, W. Va.	44.0	1901	1363
59	Mead's Creek at East Campbell, N. Y.	46.1	1935	657

Table 3--Major floods in United States exclusive of Texas--Continued

No.	Stream and location	Drainage-area, square miles	Year	Discharge, sec-feet per square mile
60	Daddy Creek, near Grassy Cove, Tenn.	46.4	1929	315
61	Baker's River, near Wentworth, N. H.	52.0	1927	288
62	Ysabel at Grande, Calif.	53.4	1916	395
63	Taughannock at Halseyville, N. Y.	56.7	1935	742
64	Rock Creek, near Pueblo, Colo.	59.0	1921	913
65	Kiowa Creek at Elbert, Colo.	60.0	1935	725
66	Chester Creek, Pa.	62.0	1843	1000
67	Jamul near Otay, Calif.	69.8	1916	259
68	San Vincente at Mouth, Calif.	74.9	1916	248
69	Bull Run at Reservoir, Oregon	77.0	1931	203.9
70	Soleduck at Fairholm, Wash.	79.0	1917	238.5
71	Dry Creek, near Pueblo, Colo.	86.0	1921	283.0
72	Sultan at Sultan, Wash.	88.0	1921	279.5
73	Salmon Creek at Meyers, N. Y.	89.2	1935	207.0
74	Putah River at Quenoc, Calif.	91.0	1904	270.0
75	Bull Run, near Bull Run, Oregon	102	1931	202
76	Wynoochie, Mantesano, Wash.	105	1924	238.1
77	San Jacinto River, near San Jacinto, Calif.	108	1927	417
78	San Jacinto River, near San Jacinto, Calif.	108	1916	278
79	Santa Ysabel, near Ramona, Calif.	109	1916	261
80	West Bijou at Johnson's Bridge, Colo.	118	1935	317
81	South Fork of Stilaquonish, Granite Falls, Wash.	119	1932	224.4
82	Willow Creek, near Morgan, Oregon	125	1903	288
83	Monument Creek, near Colorado Springs, Colo.	130	1935	385
84	Siletz, near Hogsden, Oregon	133	1921	270.7
85	San Jacinto River, near San Jacinto, Calif.	140	1927	321
86	Devil's Creek, near Viola, Iowa	143	1905	600
87	M. Bijou B/W Mouth of Wilson Creek, Colo.	151	1935	387
88	Turquillo Creek, Mora Valley, N. M.	160	1904	100
89	Sweetwater River, near Jamacho, Calif.	172	1916	250
90	Sweetwater River at Sweetwater Dam, Calif.	181	1916	251
91	Baker, near Concrete, Wash.	184	1917	200
92	Kiowa Creek, north of Kiowa, Colo.	190	1935	578
93	Esopus Creek at Cold Brook, N. Y.	192	1933	286
94	Cove Creek at Phoenix, Ariz.	200	1904	125
95	Big Sandy Creek at Rockville, W. Va.	202	1907	149
96	Siletz at Siletz, Oregon	204	1921	200
97	San Luis Rey, near Mesa Grande, Calif.	209	1916	280
98	San Gabriel River, near Azusa, Calif.	222	1916	212
99	Passumpsic River at Pierce's Mill, Vt.	237	1927	139
100	Mattole River, near Petrolia, Calif.	249	1912	223
101	Bear River at Van Trent, Calif.	262	1907	336
102	Mora River at Weber, N. M.	294	1904	94
103	San Dieguito at Lake Hodges, Calif.	299	1916	241
104	American River, near Colfax, Calif.	308	1928	179
105	New River, near New River, Ky.	312	1929	224
106	San Luis Rey, near Palo, Calif.	322	1916	233
107	Skykomish River, near Index, Wash.	355	1917	160.6
108	Deerfield River at Charlemant, Mass.	362	1927	200
109	San Diego River, near Santee, Calif.	375	1916	187
110	Calaveras River at Jenny Lind, Calif.	394	1911	177
111	San Diego River at San Diego, Calif.	434	1916	173
112	Ironton Canyon, Kingman, Ariz.	450	....	110
113	Pigeon River, near Mt. Sterling, N. C.	453	1928	87.4
114	Queets, near Clearwater, Wash.	454	1932	154
115	St. Charles River at Mouth, Colo.	482	1921	149
116	San Luis Rey at Oceanside, Calif.	565	1916	169
117	Mountain Fork of American, near E. Auburn, Calif.	622	1928	161
118	Mad River, near Dayton, Ohio	632	1913	120

Table 3--Major floods in United States exclusive of Texas--Concluded

No.	Stream and location	Drainage-area, square miles	Year	Discharge, sec-feet per square mile
119	White River at West Hartford, Vt.	687	1927	204
120	Lewis River, near Ariel, Wash.	733	1933	176
121	Canemaugh River, near New Florence, Pa.	748	1936	122
122	Emery River at Harriman, Tenn.	793	1929	190
123	Winooski River, Essex Junction, Vt.	1016	1927	114
124	Winooski River, near Essex Junction, Vt.	1070	1927	111
125	Miami at Taylorsville, Ohio	1155	1913	110
126	Little Arkansas at Wichita, Kan.	1200	....	100
127	Yuba River, Smartsville, Calif.	1220	1909	90.9
128	Conecuh River, Andalusia, Ala.	1300	1929	118
129	Cheat River, near Morgantown, Va.	1380	1888	116
130	Bijou Creek at Mouth, Colo.	1444	1935	196
131	Canadian River, French, N. Mex.	1480	1904	105
132	Santiam River, Jefferson, Oregon	1890	1909	57.1
133	Chemung River at Elmira, N. Y.	2055	1889	67.2
134	Caney Fork, Silver Point, Tenn.	2100	1929	105
135	Miami River at Dayton, Ohio	2513	1913	99.5
136	Skagit River, near Sedro Wooley, Wash.	2970	....	134.7
137	West Branch of Susquehanna River at Renova, Pa.	2975	1936	79
138	Eel River at Scotia, Calif.	3071	1915	94.4
139	Juanita River, Newport, Pa.	3354	1889	54.3
140	Mohawk at Vischer Ferry Dam, N. Y.	3385	1914	41.4
141	Miami at Venice, Ohio	3790	1913	97.6
142	Sciota River, Chillicothe, Ohio	3847	1913	67.6
143	Yadkin River at Highrock, N. C.	3930	1916	46.8
144	Kennebec at Waterville, Maine	4270	1901	51.1
145	Cape Fear at Fayetteville, N. C.	4290	1908	31.0
146	Hudson at Mechanicville, N. Y.	4500	1913	26.7
147	Black Warrior at Tuscaloosa, Ala.	4830	1900	44.5
148	Willamette River at Albany, Ore.	4840	1861	56.6
149	West Branch of Susquehanna River at Williamsport, Pa.	5682	1889	56.0
150	West Branch of Susquehanna River at Williamsport, Pa.	5682	1936	46.0
151	Delaware River at Riegelsville, N. J.	6340	1903	43.4
152	Delaware River at Trenton, N. J.	6800	1936	29.0
153	New River at Fayette, W. Va.	6850	1818	40.9
154	Pee Dee River at Rockingham, N. C.	6910	1928	30.7
155	Willamette River at Salem, Ore.	7280	1861	68.7
156	Savanah River at Augusta, Ga.	7304	1929	47.9
157	Roanoke River at Old Gaston, N. C.	8350	1877	32.9
158	Kanawha at Kanawha Falls, W. Va.	8367	1878	32.3
159	Potomac River, near Washington, D. C.	11560	1889	33.7
160	Santee River at Ferguson, S. C.	14800	1916	76.7
161	Ohio River at Pittsburgh, Pa.	19100	1763	25.0
162	Susquehanna River at Harrisburg, Pa.	24100	1936	31.0
163	Susquehanna River at Harrisburg, Pa.	24100	1889	29.3
164	Susquehanna River at Marietta, Pa.	25990	1936	30.0
165	Tennessee River at Florence, Ala.	30800	1897	14.4

Two areas designated as Zone B are shown. Although similar in runoff-characteristics, they differ greatly in the individual factors which control the resultant runoff. One of these is far inland, bordering the High Plains, where storms of great intensity are rare, and slopes and soils combine to produce comparatively light runoff. The other parallels the coast, where rainfall is both intensive and frequent, but where slopes are so flat that damaging floods are at least infrequent.

Between these two areas of Zone B lies a wide zone of higher runoff, Zone C, extending from the Red River to the Rio Grande, and broken only by the area adjoining the Balcones Escarpment in central Texas.

The area along this escarpment, shown as Zone D, is characterized by torrential precipitation, shallow soils, and steep slopes, a combination that produces extreme rates of runoff. From this area have come some of the greatest flood-discharges that have so far been recorded in the United States.

The vertical displacement along this escarpment varies from zero in north Texas to as much as 1100 feet in southwest Texas. As the warm moisture-laden winds flowing inland from the Gulf are forced upward in crossing this escarpment the ascensional movement is frequently all that is necessary to disturb the equilibrium between temperature and pressure, and cause precipitation. It is this physiographical feature that probably accounts for the greater frequency and higher intensity of rainfall that occurs in this area.

A small chart has been placed on Figure 1, which shows the probable maximum discharge that may be expected from any average drainage-area within the respective zones. Each curve represents the average condition within the zone. There are obviously small areas within each zone which should take either higher or lower runoff-characteristics than indicated by the curves. Consideration of this variability of areas should be applied to their use, and modification made as justified by local conditions.

Figure 2 has been prepared to show the variation in runoff-characteristics between different sections of the State, as reflected by the records of maximum discharge from the various streams. These data have been plotted on logarithmic paper in terms of discharge in second-feet per square mile, with the different streams indicated by separate symbols. A wide variation in the rates of runoff for the different streams may be noted, but there is also a noticeable variation in runoff-rates along the same stream, reflecting the changing conditions encountered by the stream in coming from one zone into another. The data on which this chart is based are tabulated on Table 2.

In order to show how the Texas floods compare with the outstanding discharges obtained elsewhere in the United States, Figure 3 has been prepared, whereon the data for Texas (given in Tables 2 and 3) are plotted by one symbol and those of the remainder of the United States by another. An envelope-curve, representing extreme conditions (and applicable over only a small area, Zone D) is drawn on this Figure. This curve was computed by the equation $q = 150,000/(A + 100)^{0.8}$, where q is the discharge in second-feet per square mile and A is the area in square miles. One point, representing the West Nueces River, where a discharge of 1520 second-feet per square mile was measured from 402 square miles, has purposely been avoided in computing the curve of best fit.

For areas of less than 10,000 square miles, the data for Texas stand well above anything else that has been recorded in the United States, considering the records through 1936.

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U. S. Bureau of Reclamation,
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LUNAR RAINFALL-RELATIONSHIPS: AN INQUIRY INTO A WEATHER-FORECASTING METHOD

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The manuscript for this paper was not submitted.

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THE PROBLEM OF FORECASTING SLEET FOR HIGHWAY AND INDUSTRIAL PURPOSES

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Sleet as well as the closely related phenomenon of glaze (clear ice) is one of the most troublesome types of precipitation from the standpoint of highways, transportation-interests, power-companies, etc. Its nature is, from the meteorological standpoint, as yet poorly understood. Even the definition of sleet is fraught with much confusion which unfortunately we are unable to clarify, and will pass over here. However, practically we observe sleet at the ground in various characteristic forms, commonly, for example, as: (1) Dry sleet-pellets alone, which may or may not stick together on the ground; (2) wet sleet-pellets alone, which may or may not be freezing together on the ground; (3) wet sleet-pellets with undercooled raindrops; (4) wet sleet-pellets with warm raindrops (above 32° F); and (5) sleet-pellets with wet snowflakes. Two or more of these conditions may be occurring alternately or in some succession. Obviously there are many intermediate conditions which cannot be simply classified. In the case of glaze (clear ice) on the highways, there are the contrasted types: (1) When the ground is frozen, and (2) when the ground is just 32° or a little above, but the air is colder. Also trees and other objects may be below 32° and taking on ice while the ground or highway is too warm.

The area affected by sleet or glaze at one time or during one storm is referred to as the sleet-, glaze-, or icing-belt or zone, and is generally a sort of transitional belt between a rain- and a snow-area. For the meteorologist these are difficult phenomena to understand and forecast with the detail needed by utilities because not only the atmospheric conditions proper but also the temperature and topography of the ground must be considered carefully. Frequent surface-observations from a dense network of stations, such as the airways-system, may show the surface-distribution of sleet-, ice-, and temperature-belts at successive short intervals with sufficient detail to help the affected utilities in "steering" their operation to avoid trouble by forecasting the probable movement and intensity of the sleet- or ice-belts a few hours ahead, but not with the accuracy really needed in the long run. With such surface-observations alone the sleet-forecaster is largely in the dark as to the conditions and their trend of development in the upper air where the precipitation is actually forming, or, once formed, is melting or freezing as it falls. Modern meteorology finds the seat of weather-changes in this latitude to be in the upper air, in the layers below about 10,000 or 15,000 feet as far as immediate and few-hours-ahead weather is concerned, and also in the vicinity of the base of the stratosphere as far as the day-to-day and week-to-week changes go. This means that frequent accurate upper-air observations from a sufficient network of stations are quite essential.

The present knowledge of the upper-air conditions favoring the occurrence of sleet or glaze is so vague and hypothetical that the forecasters have only crudely empirical rules for their prediction, which explains why the forecasts leave much to be desired. The sleet is forming under conditions of low dense clouds or fog, all of which prevent the taking of upper-air observations by the methods in use up to now, so that we are more ignorant of sleet-storms than of most other weather-types. The few detailed studies that have been made of the structure of the atmosphere when sleet or glaze was forming were thus handicapped by insufficient upper-air data as well as by inadequate working hypotheses of the cause of sleet. As a result much that has been written is largely speculative and open to question in the light of more recent ideas of meteorology and is also of little practical use to one who wishes to attempt detailed forecasts of these conditions. It would therefore be to little purpose to review the literature here, but a bibliography is appended for what it is worth.

Specifically, we need information on the varieties of internal structure of sleet-pellets, the vertical variation of temperature and humidity of the air when they are forming, the influence of the kind of ground-surface or objects and their temperatures on the character of the deposits, the movement and size of the synoptic areas (belts) of sleet or glaze, and the geographical and topographic relations of the storms. Once these facts are known, the forecaster will know what conditions to look for and can study prediction as a problem in itself. With the newly-developed methods of upper-air sounding by radio-meteorographs the necessary data can be obtained without difficulty; and with modern methods of analyzing such data by fronts and air-masses and the thermodynamic equilibriums of the different layers in the atmosphere, the physics of the formation of sleet and the three-dimensional weather-map situations accompanying it can be formulated in much more rigorous terms than up to now. The problem is therefore by no means hopeless. For example, we may assume that most sleet forms as typical frontal (warm-front) precipitation in the beginning; then the width of the sleet-belt and the amount of sleet-fall must be closely related on the one hand to the slope and speed of the front and to the rate of ascent, moisture-content, stability, convergence, and mixing trends of the warm upper current, and on the other hand to the temperature- and humidity-conditions of the colder air below the warm front where precipitation may occur and to the temperature and topography of the ground where the precipitation may fall. Even so, with present conditions it cannot be expected that such knowledge, if it were conclusively and even quantitatively established by much actual observation, would afford a good basis for any more than short-range forecasts up to six or twelve hours in advance. The general problem of longer-range forecasts remains to be solved. However, we may assume that for sleet, the short-range prediction will be ample.

As mentioned above, a new device, the radio-meteorograph, can give the necessary upper-air data on sleet-storms. Some suggestions as to the manner in which such data could or should be made available for sleet-forecasting may be of interest. Although the radio-meteorograph is still awaiting wide-spread introduction, recent tests by Harvard University and the Massachusetts Institute of Technology at Boston have shown its practicability for routine daily upper-air soundings. There should be enough radio-meteorograph stations in the country to make it possible to plot a number of east-west and north-south vertical cross-sections through the atmosphere to the stratosphere, at least once a day if not more in ordinary conditions, with correspondingly more frequent ascents where specially threatening situations develop. It would be helpful, too, to have regular soundings made from ships off the coasts.

The radio-meteorograph sounding has the advantages not only of being made in any kind of weather but also of quick evaluation of the results, which can be put on the airways-teletype and Weather Bureau telegraph systems and transmitted all over the country immediately, as well as being broadcast by radio. From these data the cross-sections and upper-air maps can be plotted and analyzed in conjunction with the surface-weather map, as is now being done at a few stations. As in making the regular weather-forecasts, these aids should be used as a basis for special sleet- and glaze-forecasts, by whomever made. For this purpose a single sounding per day will be insufficient, because conditions change too quickly where such a phenomenon as sleet, delicately dependent on the critical temperature of 32° F, is concerned.

To be of real value to interested utilities, a special sleet-forecast should include whether one or more of the above-listed precipitation-forms will occur, the approximate amount of precipitation, and whether glaze of certain variety and consistency is likely to form on highway and overhead transmission-lines, the duration of the storm over a certain area and the weather-conditions expected after the storm, with particular reference to the temperature and the wind.

In closing, I wish to express my appreciation and thanks to R. G. Stone of the Blue Hill Observatory for his valuable assistance in preparing this paper and for the appended bibliography.

A working bibliography of sleet and glaze

(Compiled by R. G. Stone)

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THE HYDRAULIC-MODEL STUDIES FOR THE DESIGN OF THE IMPERIAL DAM

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The manuscript for this paper was not submitted.

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RATES OF SILTING IN REPRESENTATIVE RESERVOIRS THROUGHOUT THE UNITED STATES

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For three years the Soil Conservation Service has been studying the effect of accelerated soil-erosion on silting of storage-reservoirs. More than 8400 dams and reservoirs are now in existence in the United States, exclusive of farm-ponds. They represent a capital investment of not less than $2,000,000,000. At least one-fifth of this number, representing probably three-quarters of the total investment, depend solely upon storage for their usefulness; when storage is gone as a result of silting, their value will have largely disappeared. Every State in the

United States has some developed reservoir-storage, and everywhere that studies have been made, some of this storage-capacity is being lost through silting traceable, in part at least, to accelerated soil-erosion. Thus, truly, the problem is nation-wide in its importance.

The studies under way are providing an accurate basis for planning long-term erosion-control programs to serve the needs, not only of individual farms and local agricultural communities, but also the large public and private interests which are being adversely affected by increasing loads of erosional debris. The resulting data should, in addition, prove of much value to engineers engaged in reservoir-planning, in design of silt-prevention works, and in a wide range of hydrologic studies.

To date, 55 detailed reservoir-surveys have been made in 19 states following standardized methods of survey as described in the Appendix of Technical Bulletin 524 of the United States Department of Agriculture. In addition, about 500 other reservoirs have been inspected and reconnaissance sediment-measurements recorded on a majority of them. In the brief time available here it will be possible to offer only a very condensed outline of reservoir silting-conditions in several important regions of the country.

In the Southern Piedmont Region reservoirs might be divided into three classes: (1) Channel-reservoirs without over-bank or flood-plain storage, used mainly for power by grist-mills and cotton-mills; (2) basin-type reservoirs impounding generally from 1000 to 20,000 acre-feet of water used principally for municipal water-supply, but occasionally for power and recreation; and (3) large storage-reservoirs impounding generally over 100,000 acre-feet of water and used almost entirely for hydroelectric power-development.

Ordinarily it has been considered unnecessary to make surveys of the channel-type reservoirs in this Region for reconnaissance-examination has disclosed that almost without exception they have long since lost whatever storage was originally available, and are now passing practically the entire sediment-load of the stream. Thirteen representative reservoirs of this type with dams averaging 30 feet in height were found to be completely silted at an average age of 29-1/2 years. Some of the few dams of this class recently built were filled in from one to five years.

In channel-reservoirs, storage is commonly secondary to power-head, but extensive damage to intake-valves, turbine-impellers, etc., is often a result of passing heavy sediment-loads, and has been the cause of ultimate abandonment of not a few power-plants in the Region.

Surveys of four channel-reservoirs in a stretch of 55 miles along New River in southwestern Virginia were made, however, as a special study of this type of reservoir; they have shown very high rates of silting. Fields Reservoir, the uppermost one, impounded by a 14-foot dam has lost 41 per cent of its capacity in the six years since it was built. Washington Mills Reservoir, 43 miles downstream, impounded by a 40-foot dam and having an original capacity of 2954 acre-feet, has lost 83 per cent of its capacity in 33-1/2 years. It is significant that a survey made in 1922, when the Reservoir was 19-1/2 years old, showed it was then 80 per cent filled. Calculation of the cavity-volume in the back-water area necessary for the normal flow of the stream through the Reservoir shows it is equal to approximately 20 per cent of the measured original capacity. Since the three per cent difference in capacity is within the fluctuation in total sediment-deposit due to scour and fill during alternate floods and draw-down, it is apparent that no additional permanent fill has occurred in the last 14 years and probably for a number of years prior to that. Byllesby Reservoir, nine miles below Washington Mills, with an original capacity of 8892 acre-feet, silted 60 per cent in 23 years and Buck Reservoir, three miles below Byllesby, with an original capacity of 1225 acre-feet, silted 23 per cent in 23 years. These two still have some capacity to lose and it is apparent that other dams upstream are no insurance against their losing it.

By contrast nine smaller basin-type storage-reservoirs including five in North Carolina, one in South Carolina, and three in Alabama, are silting at a composite average rate of 0.79 per cent a year. The average age of these reservoirs is 11-2/3 years, and the average total depletion of storage is 7.72 per cent. The outside limits in rates of silting, however, are 0.1 per cent a year in Lake Purdy near Birmingham, Alabama, and 2.1 per cent a year in the Spartanburg Municipal Reservoir in South Carolina, a difference of twentyfold.

Three large storage-reservoirs, typical of this class in the southeast, namely, High Rock Reservoir near Salisbury, North Carolina, Lloyd Shoals Reservoir near Jackson, Georgia, and Lay Reservoir at Sylacauga, Alabama, are silting at rates of 0.62, 0.51, and 0.52 per cent a year, respectively. This uniformity appears significant; it suggests at least that projects of this type in the Piedmont may generally be expected to silt at rates of one-half to three-quarters of one per cent a year. Many special factors which must be taken into consideration influence the useful life of such projects including minimum storage-capacity necessary for sustained utilization of each project, and the probable change in silting-rates with increasing age along a definite but yet unestablished curve. It seems, however, that present silting-rates safely indicate a useful life in excess of 100 years for these large developments.

In Texas an outstanding case of severe silting discovered by these surveys is Lake Waco on the Bosque River at Waco, Texas. Built for municipal water-supply in 1930 at an initial cost of more than 2,000,000 and storing originally 39,378 acre-feet of water, this reservoir had lost over 14 per cent of its original capacity by 1935. A resurvey made in 1936 when the reservoir was still less than six years old showed a storage-loss of 19.78 per cent, an average loss of 3.34 per cent a year, but an actual loss of over five per cent or 985,000,000 gallons of storage-space in 11 months. Since this second survey in February, 1936, the heaviest floods of record have occurred on the adjacent Brazos River. The total storage-loss to date may therefore be well over 25 per cent. If only the average 6-year rate of silting is assumed, the reservoir-capacity will be exhausted in another 24 years, but if the rate during 1935 should prevail, as it probably did in 1936, storage would be gone in another 19 years.

Other reservoirs in Texas are silting at critical rates. A small basin-type municipal reservoir at Rogers, Texas, impounding 164 acre-feet when built, has lost 23 per cent of its capacity in 12 years. This is equivalent to a loss of 1.1 inches of soil over the entire 352 acres of watershed. White Rock Reservoir at Dallas, Texas, with 18,158 acre-feet original storage, has lost 21 per cent of its capacity in 25 years.

Two reservoirs near Paris, Texas, have yielded interesting data. Lake Gibbons, the original water-supply lake for the city, stored 1414 acre-feet of water when built and has a drainage-area of 1.26 square miles. A survey made when the reservoir was 36 years old showed an average rate of fill of only 0.15 per cent a year. A larger reservoir, Lake Crook, was built 23 years later impounding 11,487 acre-feet with a drainage-area of 52.9 square miles which included the smaller lake and its drainage-area. The larger lake in 13 years has silted at an average rate of 0.49 per cent a year. The smaller reservoir had a storage-capacity of 1122 acre-feet per square mile of drainage and the larger a capacity of 223 acre-feet, a ratio of about 5:1. The corresponding difference in silting-rates is 1:3, inversely proportional to storage per square mile. This would suggest the storage-ratio as a controlling factor. Yet to be determined, however, is the ultimate effect of land-use in the two drainage-areas. In the smaller only 15 per cent is crop-land, two per cent idle land, and 67 per cent pasture and grass-land. In the larger, 33 per cent is crop-land, 10 per cent idle land, and only 38 per cent grass-land. Perhaps if these ratios were reversed the difference in silting-rates would be 1:2 or less.

Lake Taneycomo on White River, Missouri, one of the largest channel-type reservoirs in the country, with an original storage of 43,980 acre-feet, lost 46.08 per cent of its capacity in 22.4 years, an average loss of 2.06 per cent per year.

Lake Decatur on the Sangamon River, Illinois, municipal water-supply reservoir for Decatur and second largest in the State, storing originally 19,738 acre-feet, lost 14.23 per cent of its capacity in 14.2 years. Of the smaller storage-reservoirs in Illinois, Lake Bracken at Galesburg, has filled nearly eight per cent in 13 years, West Frankfort Reservoir eight per cent in ten years, and Lake Calhoun at Galva, a recreational center, 52 per cent in 12 years.

The problem of silting in Elephant Butte Reservoir on the Rio Grande is a whole story in itself. Results of several silting-surveys have been previously presented to the Section of Hydrology of the American Geophysical Union. The last survey in 1935 determined the average silting as 18,034 acre-feet per year for the 20-1/4 years since storage began, which amounts to an average annual loss of 0.68 per cent. Since, according to Fiock, approximately 5000 acre-feet or three-fourths of one per cent of the incoming silt has gone past the outlets in the dam as a result of underflow currents (L. R. Fiock, Records of silt carried by the Rio Grande and its accumulation in Elephant Butte Reservoir, Trans. Amer. Geophys. Union, 15th annual meeting, 1934, pp. 468-473), the average net output of erosional debris is 18,280 acre-feet per year from the watershed of 26,312 square miles. This is, of course, exclusive of the large volume of sediment involved in the progressive aggradation of the middle Rio Grande Valley as shown by recent valley-surveys. The annual rate of silting in Elephant Butte Reservoir declined during the period 1925-35 from a previous average of approximately 20,000 acre-feet per year. This has been due solely to decrease in the average annual inflow, the silt-content of the inflow having maintained a strikingly uniform average of 1.65 per cent by volume.

San Carlos Reservoir on the Gila River, Arizona, silted at an average rate of 0.47 per cent a year from 1928 to 1935. Black Canyon Reservoir on the Payette River in Idaho, a large irrigation-development of the United States Bureau of Reclamation, has silted at an average rate of 0.89 per cent a year during 12 years since completion.

Surveys in California have indicated generally low rates of silting. The majority of reservoirs in the State are located in mountainous regions where watershed-protection is excellent so long as the original forest- and chaparral-covers are maintained. When sudden destruction by fire or ruthless timber-cutting occurs, a case like that of Lake Harding on Santiago Creek develops. This reservoir, having a watershed floored with loose-textured granitic soils, had silted only a negligible amount until all the chaparral-cover was burned off in the summer of 1926. Following the fire, in February, 1927, a series of heavy rains occurred that caused drastic erosion of the denuded soils and practically filled the reservoir within a period of a single month.

Of the eight reservoirs surveyed in California, four, namely, Upper Crystal Springs and Upper San Leandro in the San Francisco Area, Lake Sherwood in Ventura County, and Little Rock Reservoir in Los Angeles County, show negligible rates of fill. Three reservoirs, Hodges and Morena, units of the San Diego water-supply system, and Santa Anita Reservoir in Los Angeles County, show moderate rates of fill comparable to the larger reservoirs in the southeast and one shows a critical rate of silting. This is Gibraltar Reservoir in Santa Barbara County, which has filled 29.8 per cent in 16-1/4 years, or at a rate of 1.84 per cent per year.

The number of reservoirs thus far surveyed does not represent an adequate sampling of conditions over the entire United States. A minimum of 150 standardized surveys are needed to include every major variation of reservoir-type and watershed-characteristics. Of the 55 reservoirs surveyed by the Soil Conservation Service, all but four depend almost solely upon storage-capacity for their continued usefulness. Of 47 for which comparable data are now available, continuation of present silting-rates to the point of complete filling would give a total life-span of 10 to 50 years for 17 per cent, 50 to 100 years for 13 per cent, 100 to 200 years for 36 per cent, and over 200 years for 34 per cent. By comparison, 34 additional reservoirs previously surveyed by other agencies, including a higher proportion of channel-type reservoirs, would have total life-spans of 1 to 50 years for 53 per cent, 50 to 100 years for 23 per cent, 100 to 200 years for 17 per cent, and over 200 years for 16 per cent.

If three assumptions are made to clarify the picture, first, that decrease of reservoir-capacity to 20 per cent of that originally provided will on an average terminate the useful life of a reservoir, second, that rates of silting will remain generally uniform until 80 per cent of the storage-capacities are gone, and third, that data on 81 reservoirs--47 surveyed by the Soil Conservation Service and 34 by other agencies--represent an adequate sampling of the total number in the United States, then these data indicate that: Thirty-eight per cent of existing reservoirs will have a useful life of 1 to 50 years, 24 per cent a life of 50 to 100 years, 21 per cent a life of 100 to 200 years, and only 17 per cent a life of more than 200 years. If this picture is even substantially correct, it shows an urgent need for remedial measures of soil-conservation and silt-detention to protect existing developments along with more considered planning of future water-storage projects in the light of watershed-conditions.

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SOME OBSERVATIONS ON WELL-CHARACTERISTICS

W. E. Code

In 1928 a program was started by the Colorado Agricultural Experiment Station on the study of ground-water development with a view towards improvement of pumping machinery and well-practice. The study of irrigation-wells disclosed that metal-cased wells ranged in diameter from 12 inches to 48 inches and the corresponding approximate prices from $3.50 to $17.00 per foot for casing and drilling. It was quite apparent that the larger wells, in general, had a higher specific capacity than the smaller ones, but little was known regarding the relationship existing between the sizes and whether the larger sizes were justified economically. As this relationship was of importance, a plan was decided upon which had for its purpose the obtaining of data on the range of well-sizes in general use.

Economic factors are difficult to evaluate. It may be shown that the specific capacity of two 12-inch wells is greater than that of one 48-inch well. The mutual interference, however, can be determined only by tests of a somewhat complicated character, and the distance between the wells for a single pumping-unit cannot be great, as the cost of the connecting piping would be excessive. In areas where the radius of influence is great and wide spacing is desirable, unit power-plants are to be considered. With more than one well in a system the plant must be designed so as to permit pumping from all wells with one pump. If the conditions permit the use of a horizontal centrifugal pump, the diameter of the well need not be much greater than that of the suction-pipe. If a turbine-pump is used, then the well needs to be of a size sufficient to receive the bowls and in a battery-system sufficiently larger to receive also the incoming siphon-pipe. The problem for consideration was whether greater diameter would be justifiable under the conditions.

An approach to the problem was considered which would involve little field-expense. This plan consisted of permeability-tests on gravel-samples obtained from wells where discharge-drawdown data had been taken. The writer collected about half of the 61 samples tested; the rest were obtained from well-drillers by a specified method. Wells were selected to include many sizes between 12 and 48 inches. It was hoped that if some criterion could be discovered so that the relationship between the physical and permeability-characteristics could be determined, then there might be an opportunity to apply the criterion to the well-sizes.

The plan was a failure for many reasons which became apparent as the work progressed. The failure was caused, in part at least, by poor samples, well-variability, and varying permeability-results. However, the information derived from the work was of some value to the writer and is presented for what it may be worth.

Laboratory permeability-studies--The samples obtained weighed approximately 25 pounds. To avoid loss of fine materials in the field, the drilling-buckets were dumped into a tube and the samples taken after pouring off the water and mixing. The samples usually represented materials from a foot-depth or less in the well, that is, they were not composites. Some gravels contained stones greater than two inches in diameter which were refused at the time of sampling. Before the screening- and permeability-tests were made, the samples were passed over a 1/2-inch-mesh screen. Specific gravity of the particles was obtained by means of a Le Chatelier flask. The apparatus for determining permeability was patterned after that used by O. E. Meinzer [see 1 under "References" at end of paper] except that the cylinder diameter was four inches and the length of sample 24 inches. The cylinder was filled in two or three stages, and each stage was followed by rapping with a light wooden stick until the whole was consolidated to about the maximum density. The cylinder was then weighed and the porosity determined. The problem of maintaining a uniform water-temperature was difficult because of the lack of facilities. Most of the work was done in winter in an overheated basement, and no control over the room-temperature was possible. Water at a temperature of 42° to 45° F was obtained from the city mains for the first 19 samples, and, for the other samples, water was used from a 250-gallon tank on the laboratory floor. With this latter arrangement the temperature-variation during a test was very much less. The greatest difficulty in this respect occurred during the test of a sample of low permeability, when the water in the connecting hoses was affected considerably by room-temperature. The temperature of the outflow was observed, and the results were corrected to 60° F.

The transmission-constant K, which was computed from the results, is that of Slichter. It is defined as the quantity of water in cubic feet passing through a column of gravel, one square foot in area and one foot high, in one minute. The gradients observed on the first 19 samples varied from 9 to 198 per cent. After that the only one observed was the 100 per cent gradient. These data gave check-results on the operation of Darcy's law of flow through soils.

The first three samples were run several times with the following results in values of K: No. 1--0.0206, 0.0219, and 0.0167; No. 2--0.0094, 0.0054, and 0.0053; No. 3--0.0342, 0.0435, 0.0083, and 0.0123. The last one showed a variation of about 400 per cent. These are wide deviations and, since the capacity of a well varies as K, a permeability-test of a drill-sample could not be considered reliable. No duplicate runs were made on the remainder of the samples.

Frequently, during a permeability-test, the rate of flow constantly diminished when observed over a period of time. With sample No. 32, the rate decreased from 10.1 to 9.3 cubic cm per minute in 1-1/4 hours, and with No. 56 the rate decreased from 24.5 to 21.3 cubic cm per minute in 6-1/2 hours. To explain this decreasing rate, it was assumed that the flowing water was causing a rearrangement of the particles to form a more dense mixture. There was also a slight possibility that the two per cent passing the 200-mesh screen might have been composed of colloidal clay which swelled when becoming wet.

A further study was made of the clogging action by using Ottawa sand in connection with a

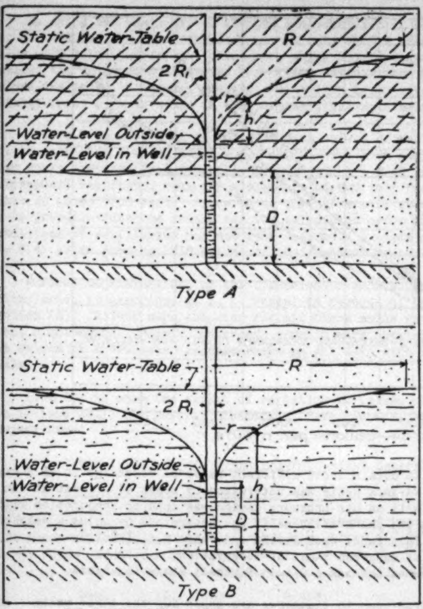

FIG. 1—CONDITIONS FOR TYPES A AND B WELLS

check on the temperature-correction formula and grain-size. It was found that this sand showed similar characteristics. The initial flow was about 990 cubic cm per minute, and two days later the flow had dropped to about 645 cubic cm per minute. No flow was allowed between tests. The next trial, after emptying and drying the sand, began with a flow of 846 cubic cm per minute. Water was allowed to flow slowly through the sample and 18 hours later the flow was about 800 cubic cm per minute. Forty-two hours later the flow was about 710 cubic cm per minute. Only slight variations were found in short periods of time. The porosity of the first sample was 34.3 per cent and of the second 32.4 per cent. These variations, of course, preclude accurate hydraulic data.

Another study of the clogging action was made by using an angular sand of approximately the same size as the Ottawa sand. With this the rate of flow decreased from 1466 to 1322 cubic cm per minute in two hours and to 1222 in 22 hours.

Slichter accounted for the decreasing percolation rate as being caused by bacterial action and used formalin to prevent such growth. In the cases described it is doubtful if the bacteria would grow at such a rapid rate as to cause large changes in short periods of time.

Subsequent well-test data revealed that the values of the transmission-constant as obtained in the field were about 10 or 20 times as great as those obtained in the test-cylinder. Therefore, it was decided to run 15 of the gravel-samples again in as porous a state as possible. Increases in porosity of from 18 to 70 per cent were obtained which increased the values of the transmission-constant three to six times in most cases, and in one case 26 times. The values remained 1/4 to 1/10 of the field-determinations.

Field-determination of transmission-constant--A field experiment was conducted in the Arkansas Valley about 30 miles east of Pueblo for the purpose of obtaining data on the relation of size of well to yield. Three wells, approximately 25 feet apart and 46 feet deep, were drilled through 19 feet of clayey soil into a fairly uniform mass of coarse gravel. The water-table stood about 10 feet from the surface or in the clay. This condition resulted in two well-types, according to whether the draw-down extended below the clay or not. M. R. Lewis [2] described and provided capacity-formulas for both types of wells which he calls A and B. The wells are shown in Figure 1. To a draw-down of 10 feet, they function as type-A wells and below this as type-B.

The diameters of these three wells were 12, 18, and 24 inches, respectively. A well-point was driven to a depth of 35 feet within a foot or two of each casing. Its exact relative location was not ascertainable because of the deviation of the pipe from the vertical. Three other observation-wells driven into the gravel were located on either side at distances of 100, 300, and 600 feet. All three wells were in a straight line paralleling a railroad which runs in a direction approximately following the river-bottom. On the north side, at a distance of about 700 feet, the bottom-lands are bounded by mesa-lands not underlain by gravel. The river is on the south side, about 3/4 mile distant. In addition, observations were possible on two irrigation-wells 1255 and 1745 feet distant in an upstream direction. The use of these observation-wells was not intended for critical study of the draw-down curve because they were insufficient in number and the personnel was limited to one man.

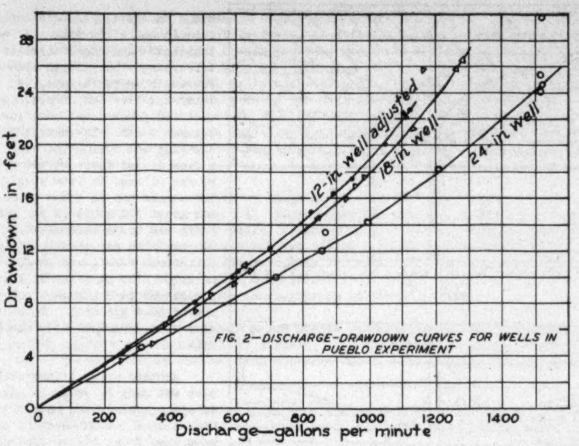

FIG. 2—DISCHARGE-DRAWDOWN CURVES FOR WELLS IN PUEBLO EXPERIMENT

The usual procedure of pumping was to obtain three different rates of discharge in an 8-hour period. The water-level in the 18- and 24-inch wells was determined by means of a float at the end of a steel tape, but in the 12-inch well an air-pressure device was used in conjunction with a mercury-manometer. The water-level in the observation-wells was determined by using a weighted metal tube at the end of a steel tape. This tube, open at the end, made a distinctive sound as it met the water-surface. At the close of each run a set of observations was taken, which required about 20 minutes. Water was measured through a 9-inch Parshall measuring-flume.

In Figure 2, the relationships of draw-down to discharge are shown for the three wells. In the case of the 12-inch well, it was necessary to finish it at a depth three feet less than the others. For this reason the curve shown was adjusted by adding a correction of 3/34 to the capacity. From these curves for draw-downs to 20 feet, the 18-inch well had a five per cent and the 24-inch a 24 per cent greater capacity than the 12-inch well. The relative increased yield of the 18-inch well remained the same at a draw-down of 26 feet, but the 24-inch well increased to 30 per cent. The probable reason for the change was that the head-loss at the casing was less for the larger well.

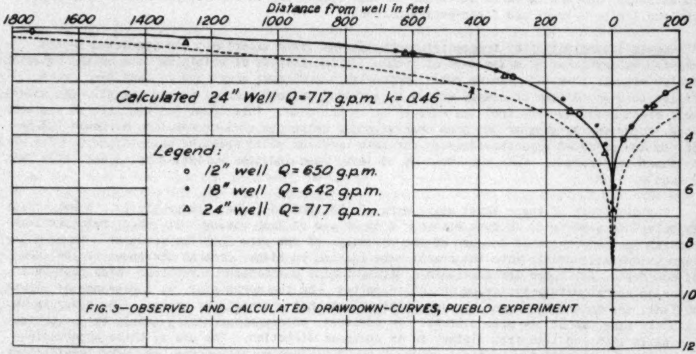

FIG. 3—OBSERVED AND CALCULATED DRAWDOWN-CURVES, PUEBLO EXPERIMENT

By using the Lewis type-A formula and substituting the conditions for a discharge of 717 g.p.m., and the observed draw-down in the well of 9.9 feet, the value of K equals 0.449. If a value of 9.0 is used for the draw-down, which should compensate for the loss of head through the casing, the value of K is 0.493. For these calculations R was assumed at 2000 feet. If smaller values are taken, K becomes smaller. Attention is directed to these assumptions because the highest value of K obtained in the permeability-experiments was 0.108.

Figure 3 shows a plot of the draw-down curves of the 12-inch well when pumping 650 g.p.m., the 18-inch when pumping 642 g.p.m., and 24-inch when pumping 717 g.p.m. For comparison a draw-down curve computed from the well-formula with K = 0.46 is also plotted. A curve using K = 0.41 corresponds reasonably well for a distance of 600 feet from the well but rises above the water-table at about 1000 feet. Since these curves were obtained only after about 2-1/4 hours pumping, it is probable that the reason for the calculated curve not agreeing more closely was because conditions of equilibrium had not been reached. A check on the 24-inch well with the value of K = 0.41 after pumping 1210 g.p.m. for 8-1/2 hours seems to substantiate this conclusion.

Further determinations of the transmission-constant were made by using the formula by G. Thiem, which is described by L. K. Wenzel in reports of the thirteenth annual meeting of this Section [3]. Values were computed for all these wells for the longest pumping-period, which was about eight hours. Fairly concordant results were obtained but the variation was considerable. The values of K decreased in most cases as the data were taken at greater distances from the wells.

In order to show the extent of variation in values of K, the following results taken from the 18-inch well, for several discharges, make comparisons possible between different lengths of pumping-time.

Table 1--Values of transmission-constant determined from data on 18-inch well

Direction	a	a'	K		
			265 g.p.m. after 7 hours' pumping	475 g.p.m. after 2 1/4 hours' pumping	642 g.p.m. after 2 hours' pumping
East	100	300	0.418	0.402	0.388
	100	600	0.406	.....	0.425
	300	600	0.385	.....	0.500
West	25	53	0.543	0.562	0.549
	25	152	0.553	0.549	0.552
	25	352	0.495	0.497	0.502
	25	652	0.472	0.487	0.487
	53	152	0.571	0.532	0.554
	53	352	0.478	0.475	0.486
	53	652	0.454	0.467	0.472
	152	352	0.408	0.418	0.420
	152	652	0.400	0.430	0.425
	352	652	0.395	0.444	0.429

The reverse sequence of values to the east, shown in the last column, is probably caused by errors in observation as other computations do not substantiate this condition. Wenzel found increasing values instead of decreasing values which he believes were caused by conditions not having reached equilibrium, although in his work the observations were taken at the end of a 48-hour pumping-period. He states that the conditions near the well are probably closer to equilibrium than at distant points. Owing to this lag, the altitude of the depression-cone is too high at distant points and the expression (S - S') in the denominator makes the values of K (he used P, coefficient of permeability) too small. However, the values should become smaller as S' is chosen farther away instead of larger as he has stated. This is the condition found in the experiment discussed here. It is believed that his theory is substantially true, that the values of K taken from observations nearest the pumped well are more nearly correct; however, curves computed with these values in the capacity-formula do not fit even approximately the observed conditions in the well.

For purposes of determining the approximate value of the transmission-constant as it relates to the well-capacity formula, the minimum value obtained at the distances used in the

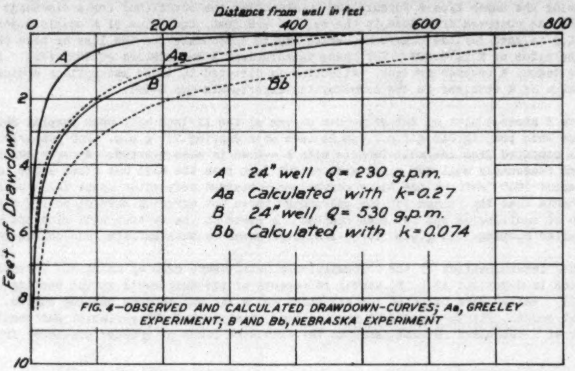

FIG. 4—OBSERVED AND CALCULATED DRAWDOWN-CURVES; Aa, GREELEY EXPERIMENT; B AND Bb, NEBRASKA EXPERIMENT

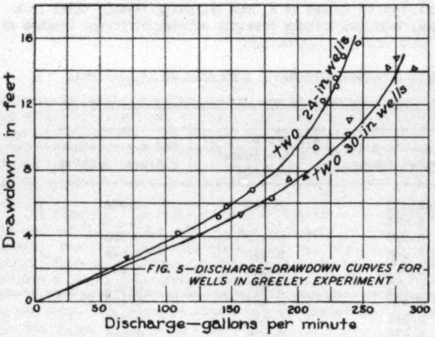

FIG. 5—DISCHARGE-DRAWDOWN CURVES FOR WELLS IN GREELEY EXPERIMENT

Nebraska study would more nearly fit the conditions within a few hundred feet of the well. In Lewis' type-B formula, the minimum value determines the radius of influence at about 325 feet, but when R is taken at 1000 feet, which is approximately the observed condition, an average value of the permeability-coefficient (P equals 796) is obtained. The computed curve is about 0.8 foot lower than the observed at points within 500 feet of the well. The data are shown in Figure 4.

Another similar experiment of less value was made near Greeley, Colorado. This study was on a battery of five wells of which two were 24 inches, two were 30 inches, and one was 40 inches in diameter. The wells were drilled about 70 feet apart. The gravel-formations were interrupted by several layers of clay, and, to test only the top 16-foot gravel-stratum, it was necessary to backfill the wells to a point within the first clay-stratum.

Figure 5 shows the discharge—draw-down curves for the 24- and 30-inch wells in the Greeley experiment. They are drawn as a mean curve through all the points of both sizes.

Tests of the gravel at maximum density for permeability gave values of the transmission-constant varying from 0.0004 to 0.0121; a fair average was 0.005. Draw-down curves calculated with the type-B well-formula require a value of K of about 0.27 to correspond with the observed value of R. This curve falls much below the observed draw-downs near the well which was also the condition found in the Pueblo experiments.

Values of K computed by Thiem's method range from 0.37 to more than 0.6 according to whether the data are taken close to or at a distance from the well. In this experiment the low values are from the data taken close to the well as found by Wenzel but the reverse of that found in the Pueblo experiment. It appears that the values of the transmission-constant by Thiem's formula are too large and those obtained by the permeability-cylinder too small, being about 1/50 of the field-observations.

The failure of the Thiem's formula to give reasonably constant values of the transmission-

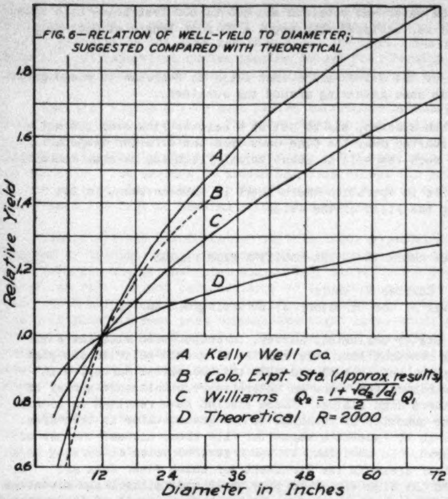

FIG. 6—RELATION OF WELL-YIELD TO DIAMETER; SUGGESTED COMPARED WITH THEORETICAL

constant and of the well-formula to fit observed data is believed to be due to the formulas not being strictly applicable. Probably some time-factor needs to be incorporated in the formulas of both well-types as is shown by the investigations of C. V. Theis [4].

It was impossible to gather sufficient data to prove a relationship between the capacities of the various sizes of wells. More experiments would be needed to establish this relationship, because of the physical impossibility of drilling two identical wells which will have identical characteristics. Enough data were obtained to place in doubt the theoretical relationship as given in Turneaure's and Russell's discussion [5]. Figure 6 shows several curves giving the relationship of well-size to capacity. Two are empirical, and the third is based on well-formulas with the assumption that the radius of influence remains constant. The Colorado experiments are plotted as a dashed line. The 12-inch size is used as a base, and those below that size were obtained in tank-experiments at the Colorado Experiment Station. It will be noticed that the Kelly formula fits most closely the Colorado data.

Summary--Observations indicate that the formulas for well-yield are not strictly applicable.

Thiem's formula, which appears to be based on the same formulas, does not yield correct results due to this defect.

Well-diameter relationships cannot be theoretically calculated because of the well-formula defect and the methods used by drillers in sinking the medium-size holes makes them more efficient than the small or large holes.

Permeability-determinations by laboratory-methods, at least in the Colorado experiments, were of very little value.

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DISCUSSION

H. P. BOARDMAN (University of Nevada, Reno, Nevada)--Many years ago (in 1892) I spent several months in the employ of the Memphis Artesian Water Company. One of my duties was to meter the flow in all of the wells then in operation, about 40, using for that purpose an adaptation of the Haskell current-meter, lowered down the well-casing to a position a little below the tunnel-connection. The wells were all connected by a tunnel-system with the wet wall of the pump-house.

The artesian stratum from which the water was obtained was 400 to 500 feet below high water of the Mississippi River, and each well was equipped with about a 50-foot length of Cook well-strainer.

It was common occurrence for some of the 6-inch and 8-inch wells to decrease in yield greatly at times, undoubtedly because of fine sand gathering around the strainer.

The remedy, which was practiced with success, was to set up a well-derrick over the well and flush back with hydrant-pressure clearing away the fine sand from the strainer temporarily. This was usually effective in bringing back the well to about normal yield for several months.

I wonder if there are not many wells in operation where there is some movement in the supply-stratum, of fine sand, affecting the yield of the well.

AMOUNT OF GROUND-WATER RECHARGE IN THE SOUTHERN HIGH PLAINS

Charles V. Theis

(Published with the approval of the Director, U. S. Geological Survey)

For the last six years the United States Geological Survey, in cooperation with the State Engineer of New Mexico, has been making somewhat intensive studies of ground-water in the part of the High Plains that lies in New Mexico, and in 1933 and 1934 the Geological Survey, with funds allocated by the Public Works Administration, made an extensive reconnaissance-survey of the ground-water conditions in the southern High Plains. These studies have resulted in considerable data that throw much light on the quantity of recharge to the ground-water in this area. An estimate of the quantity of recharge is of immediate value for this area, because the use of ground-water is constantly being increased. In addition, it has a general value in serving as a criterion for estimating recharge in other areas in the Southwest for which fewer data are available. Estimates of the recharge in the High Plains as previously made without the advantage of quantitative data have ranged from less than three or four inches a year [see 1 of "References" at end of paper] to less than six inches [2]. The work of the last few years indicates they should be greatly reduced.

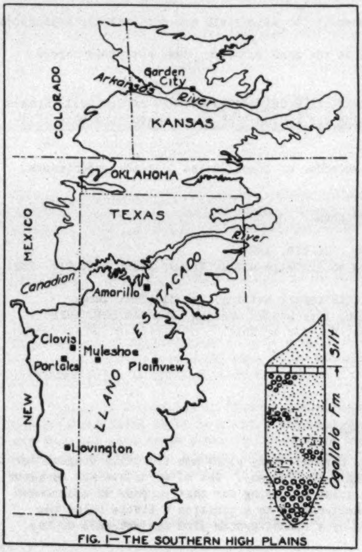


FIG. 1—THE SOUTHERN HIGH PLAINS

Hydrologic description of southern High Plains--The southern High Plains as here considered extend southward from the Smoky Hill River, in western Kansas, through the Oklahoma and Texas panhandles, and include adjacent parts of Colorado and New Mexico, covering an area of about 70,000 square miles. The part south of the Canadian River is the Llano Estacado, or Staked Plain, and has an area of about 35,000 square miles. Because this part is a single hydrologic unit, the present discussion will deal more particularly with it, but the general statements to be made appear to be applicable also to the remainder of the southern High Plains.

The main ground-water body in the southern High Plains lies in the Ogallala formation, of Pliocene and perhaps Miocene age. A general diagrammatic section is shown in Figure 1. The formation is variable laterally but consists of four types of sediments, namely: Gravel found in old stream-courses throughout the section but most prominent near the base in old pre-Ogallala valleys; unbedded and unconsolidated fine sand and silt, which make up the bulk of the formation; cemented zones of calcareous fine sand and silt, differing from the last only in cementation and forming caliche zones; and finally at the top of the formation a limestone several feet thick, generally called "caliche" but a true limestone of considerable purity. Overlying this limestone in most of the area is a deposit of fine sand or silt, reaching a thickness of over 100 feet, which has been correlated with the Pleistocene loess in Kansas and is probably of the same age throughout the area. The water-bearing Ogallala deposits rest generally on impervious shales ranging in age from Permian to Cretaceous. The surface of these pre-Ogallala beds slopes east and east-southeast about ten feet to the mile.

The High Plains are in most places surrounded by scarps a few hundred feet high reaching down to pre-Ogallala rocks. The water-body in the Ogallala is thus raised above and isolated from the ground-water in contiguous areas. The surface of the Plains, and particularly the Llano Estacado, is largely unscored by erosion. It slopes also east and east-southeast about ten feet to the mile. The surface is smooth and flat except for a few sand-dunes and for numerous sinks in the surface--"dry lakes" or "buffalo wallows"--from a foot or two to over a hundred feet deep and from a few feet to several miles in diameter.

Nearly all the precipitation on this area, especially on the Llano Estacado, is either discharged by transpiration and evaporation within a short distance of where it fell or seeps to and recharges the ground-water body. Only close to the few narrow-valleyed streams does any water run off. A good part collects as ephemeral ponds in the depressions, where it usually, but not in all localities, remains through months of drought. To penetrate to the ground-water the precipitation must pass through the tight loess-cover and through the dense but jointed limestone capping the Ogallala. In a few areas sand-dunes cover the surface, and in these places recharge is more favored. The average yearly precipitation ranges from 14 inches in the southwestern part of the area to 22 inches in the northeastern. It occurs preponderantly as summer showers and hence at the most inopportune time for rainfall-penetration.

The water-table in the central part of the High Plains lies about halfway between the surface of the ground and the base of the Ogallala. Like the ground-surface and the floor of the water-body, it slopes east or east-southeast about ten feet to the mile.

Natural discharge of the ground-water occurs to a small extent in a few water-table lakes in depressions in the High Plains, but largely it must occur as seeps and springs at the eastern escarpment of the Plains. However, there are very few springs of any size and little evidence in the character of the vegetation of a great amount of seepage.

Estimates of recharge--Before development, the ground-water body of the Llano Estacado was in dynamic equilibrium; the average recharge was balanced by an equal amount of natural discharge, and these in turn determined the rate of ground-water flow. Hence, the recharge can be estimated by making tests of the rate of ground-water flow. This line of attack is probably the most suited for obtaining a general estimate, because the flow at any locality tends to integrate the effects of unequal increments of recharge at different times and different places.

The most obvious method of estimating recharge by the rate of ground-water flow is to estimate the amount of flow across a certain cross-section and to divide this by the tributary area. The tributary area can be determined where maps of the water-table are available and sometimes on geologic evidence alone. The flow can be determined by Darcy's law if the slope of the water-table and the permeability and the cross-section area of the saturated part of the aquifer are known. In turn the permeability can be determined by laboratory-tests of samples, or field-tests by pumping. In two localities in the part of the Llano Estacado in New Mexico these factors are approximately known.

The first of these localities is in the vicinity of Portales, New Mexico. Here an eastward-trending depression in the High Plains surface and in part in the floor of the water-body causes the flow from a considerable area to be discharged through a ground-water valley. On combined geologic and hydrologic evidence, the area tributary to a cross-section of this valley through Portales has been estimated at 850 square miles [3]. The permeability of the aquifer has been estimated from pumping-tests. On generous estimates of the width of valley serving as an outlet, and of the thickness of the aquifer involved, the total flow has been computed as 24,000 acre-feet a year. This divided by the tributary area indicates a recharge of about 0.5 inch a year. A line of sand-dunes north of the valley which has been shown by water-level fluctuations to be very effective as a recharge-area makes recharge-conditions more favorable here than in most other parts of the High Plains. As all estimates entering into the computations were made generously large, it appears that the recharge in this favored locality is probably half an inch a year or less.

The second locality where such data are available is in Lea County, New Mexico. Twenty-three samples of material taken at the outcrop of the Ogallala formation on the western edge of the County had coefficients of permeability ranging from 15 to 125 and averaging 60. A pumping-test made in the eastern part of the County indicated a permeability of 325. As there is some evidence that some of the more permeable material was not exposed at the outcrop and hence could not be sampled, the figure for permeability determined from sampling may be too small. On the other hand, there is some evidence that the coefficient determined by the pumping-test may be too large. The flow past a contour of the water-table 45 miles long, running through the town of Lovington, may be computed as 8000 acre-feet a year if a coefficient of 60 is used, or 43,000 acre-feet if a coefficient of 325 is used. The tributary area is about 1200 square miles. The computed recharge using the smaller coefficient of permeability is about one-eighth of an inch a year, and using the larger coefficient about two-thirds of an inch [4]. The true recharge probably lies between these two figures.

A second method for estimating recharge is by the fluctuation of the water-table. In the western part of the Llano Estacado the water-table is so far beneath the surface that there is no loss by transpiration, and the recharge is small. Under such conditions the discharge by ground-water flow is nearly constant, because the governing factors--the slope of the water-table and the transmissibility of the aquifer--do not change significantly under natural conditions. The process of recharge, on the other hand, is intermittent. As a consequence in drought, when recharge fails, the water-table falls. It must fall at a rate sufficient to yield the average amount of water normally flowing from the area or, in other words, at a rate which when multiplied by the specific yield equals the average recharge.

Figure 2 shows the average fluctuation of water-levels in a group of eight observation-wells and the daily precipitation in Lea County for a period of 21 months. These wells were chosen to eliminate as far as possible the effects of pumping or other artificial disturbances. The specific yield for the area may probably be taken as ten per cent--that is, a fall of water-level of one inch is equal to a loss of water of 0.1 inch. Using this figure, we find that the average drop in water-level in August and September, 1932, was at a rate of 3.7 inches a year, which is equivalent to 0.37 inch of recharge a year. Similarly in May and June, 1933, the water-level fell at a rate of 2.5 inches a year, in September and October, 1933, at a rate of 4.21 inches, and in December, 1933, and January, 1934, at a rate of 2.74 inches a year, equivalent to indicated rates of recharge of 0.25 inch, 0.42 inch, and 0.27 inch, respectively.

In and after rainy periods the water-level rises.. By making some assumptions concerning time-lag in the effect of rainfall upon the water-table, correlations between rises of water-table and rainfall can be made. It is evident from the foregoing discussion that the amount of rise after a rain should be added to what would have been the normal fall of the water-table had there been no rain. If we use the maximum rate of fall shown by the record, that is, 4.21 inches

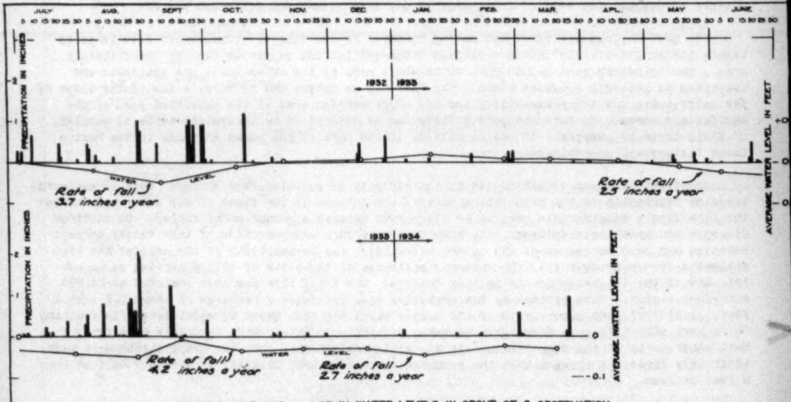
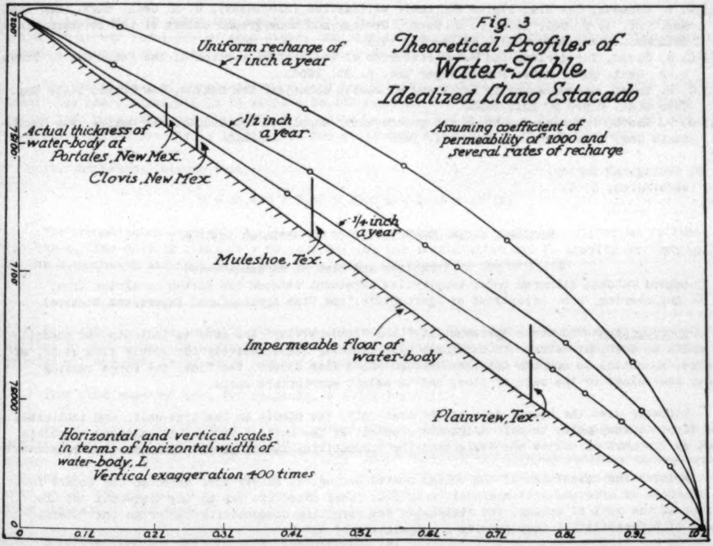


FIGURE 2 - AVERAGE CHANGE IN WATER LEVELS IN GROUP OF 8 OBSERVATION WELLS AND DAILY PRECIPITATION IN LEA COUNTY, N. MEX., JULY 1932 TO MARCH 1934

a year, as a base on which to superimpose actual rises in water-level due to rains, we obtain the following figures. Between readings in September and October, 1932, a virtual rise of 0.91 inch occurred as a result of five inches of rainfall. This is equivalent to 1.82 per cent of the rainfall. Similarly, in August and September, 1933, a virtual rise of 0.77 inch represented 1.54 per cent of the five inches of rain that fell at that time. If these percentages are applied to the normal annual rainfall of the area--14 inches--a recharge of about 0.25 inch a year is indicated. In the entire year 1933 the rainfall almost exactly equaled the normal for the area. In this year the water-level declined 0.79 inch. If the flow, without recharge, would produce a decline of 4.21 inches in a year, the decline of only 0.79 inch appears to represent an annual recharge of about one-third of an inch.

Finally, some evidence on the problem may be obtained from a consideration of the shape of the water-body in the Llano Estacado. This water-body may be idealized by considering it to occur in a uniformly permeable mass of sediments which rests on an impermeable uniformly sloping plane, with recharge occurring uniformly throughout its extent and with discharge taking place at its lower end. Theoretical profiles of such a water-body can be computed. Typical profiles are shown in Figure 3. The theoretical equations indicate that the thickness of the water-body at any point is dependent on the slope of the floor and the ratio between the amount of recharge and the permeability of the aquifer. Both vertical and horizontal scales on Figure 3 are given in terms of the width of the water-body, L. The average slope of the floor of the water-body in the High Plains is about ten feet to the mile, or 0.002. During the general investigation of the ground-water in the High Plains the permeability of many samples of material was tested. The coefficient of permeability of the coarser, bedded sediments of the Ogallala formation ranged between 80 and 1100 and averaged about 450. That of the denser unbedded sediments ranged from 1 to 485 and averaged 75. If we consider the average permeability of the Ogallala aquifer as 1000, in order to eliminate any chance of underestimation, the curves shown represent recharge-rates of one-fourth, one-half, and one inch yearly. For comparison, there is shown on this diagram in the approximately correct location and to the scale of the diagram, the actual thickness of the water-body in four localities where it is believed to be locally greatest. Each of these is slightly smaller than the theoretical thickness at the same place if the recharge is half an inch a year. At Portales, New Mexico, there is an actual thickness of about 80 feet of water-



bearing sediments compared to a theoretical 110 feet; at Clovis, New Mexico, an actual thickness of 110 feet compared to a theoretical 115 feet; at Muleshoe, Texas, a probable actual thickness of somewhat less than 195 feet compared to a theoretical thickness of 195 feet; and at Plainview, Texas, an actual thickness of about 250 feet compared to a theoretical thickness of 270 feet.

Although no one of the above computations is above criticism, yet all assumptions made and data used appear logical in the light of our present knowledge, and where some doubt is involved a conscious attempt has been made to use data that tend to exaggerate rather than to minimize the recharge. The computations involved number 14 and fall into three main lines of approach and a fourth variant line. All converge on a figure of somewhat less than half an inch a year for the average annual recharge to the ground-water in the southern High Plains.

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SPECIFIC WATER-CONDUCTIVITY OF AN ARTESIAN AQUIFER

O. W. Israelsen and Elmo R. Morgan

(Based on data gathered under cooperative agreement between the Bureau of Agricultural Engineering, U.S. Department of Agriculture, and Utah Agricultural Experiment Station)

Introduction--The terms "permeability" and "conductivity" are used to indicate the capacity of soils to transmit water. To designate this capacity quantitatively for steady flow it is, of course, essential to specify the area through which flow occurs, the time, the force causing flow, the volume or the mass of flow, and to select appropriate units.

Slichter used the square foot as the area-unit, the minute as the time-unit, and implicitly the force corresponding to unit hydraulic gradient as the unit of force. He selected the cubic foot as the unit of volume and designated the conductivity-factor as the "Transmission-constant."

Meinzer and associates of the United States Geological Survey also selected the square foot as the unit of area and unit hydraulic gradient. They chose the day as the time-unit and the gallon as the unit of volume, and designated the resulting conductivity-factor as the "Coefficient of permeability." They specify a temperature of 60° F.

Experimental evaluation of these conductivity-factors is accomplished by obtaining a steady flow and applying the equations of Darcy and continuity to the measured elements of time, volume, and driving force per unit-mass--the latter element being proportional to the hydraulic gradient.

In 1928 Gardner, Israelsen, and McLaughlin [see 1 of "References" at end of paper] introduced a conductivity-factor more readily applicable to the use of the basic concepts of potentials and potential gradients which necessitates explicit use of the force of gravity per unit-mass (g) in the combined flow-equation of Darcy and continuity. Israelsen designated this factor as the "Specific water-conductivity" [2] and defined it as: "The volume of water that will flow in unit-time through a soil-column of unit cross-section area due to the driving force per unit-mass corresponding to unit potential-gradient."

Rectilinear flow--Symbols used are as follows:

A = gross area of soil-surface normal to flow (square feet)
g = force of gravity per unit-mass or acceleration due to gravity (feet per second per second)
I = the hydraulic gradient (ratio loss of head to flow-length)
Q = volume of flow per unit-time (cubic feet per second--also gallons per minute)

k_s = transmission-constant proposed by Slichter (cubic feet per square foot per minute for unit hydraulic gradient)
P = coefficient of permeability proposed by Meinzer (gallons per square foot per day for unit hydraulic gradient)
k = specific water-conductivity proposed by Israelsen (cubic feet per square foot per second for unit potential-gradient)

We may write from Darcy's law and the equation of continuity

$$Q = k_s\ I\ A \tag{1}$$

$$Q = P\ I\ A \tag{2}$$

$$Q = kg\ I\ A \tag{3}$$

It is evident by comparing equations (1), (2), and (3) that the conductivity-factors k_s, P, and k are linear functions of each other; and also that k_s and P have the physical dimensions of length divided by time, whereas k has physical dimensions of time only.

The coefficient of permeability, P, and the specific water-conductivity, k, differ as follows: (a) The P time-unit is 24 hours = 86,400 seconds; (b) the P unit of volume is gallons rather than cubic feet and therefore 7.48 units to 1 as 1 cubic foot = 7.48 gallons; (c) the acceleration due to gravity is implicit in the P-quantity and explicit when k is used.

It, therefore, follows that

$$P = 86,400 \times 7.48 \times 32.2\ k = 2.08 \times 10^7 (k) \tag{4}$$

The transmission-constant, k_s, and the specific water-conductivity, k, differ as follows: (a) The k_s time-unit is 1 minute = 60 seconds; (b) the acceleration due to gravity is "implicit" in the k_s-quantity and "explicit" when k is used. It therefore follows that

$$k_s = 60\ kg \tag{4'}$$

Equations (1), (2), and (3) show that for rectilinear flow, the measurement of the quantity of flow in unit-time, the hydraulic gradient and the gross area through which flow occurs will provide all the data required to compute either of the conductivity-factors.

Thus from equation (3), for instance, $k = Q/g\ I\ A$.

Radial flow to wells--When water is pumped from a well in which the casing penetrates the entire thickness of an artesian aquifer, the flow to the well comes from all directions. It is assumed that when the pump-discharge is steady, water flows in the aquifer radially to the well, through each of an infinite number of vertical concentric equipotential cylindrical surfaces, each one having an average height equal to the thickness of the aquifer at a certain distance from the axis of the well.

Supplementing the symbols used hereinbefore, let

h and h' = respective draw-downs or lowering of the piezometric surface at the two observation-wells (feet)
r and r' = respective distances from axis of the pumped well to two observation-wells (feet)
f = the ratio of soil pore-space to its total volume
t = average thickness of the artesian aquifer (feet)
q = discharge of the pump which equals the flow into the well (cubic feet per second)
dh/dr = the hydraulic gradient at any radius r.

The meaning of some of the above symbols is shown graphically in Figure 1, which shows also the radial direction of flow of the water in the artesian aquifer.

According to Darcy's law, the velocity at any distance r from the axis of the well is proportional to the hydraulic gradient. Therefore, assuming k is a constant in the cylindrical surface in the aquifer of radius r, it follows that

$$v = (kg/f)\ (dh/dr) \tag{a}$$

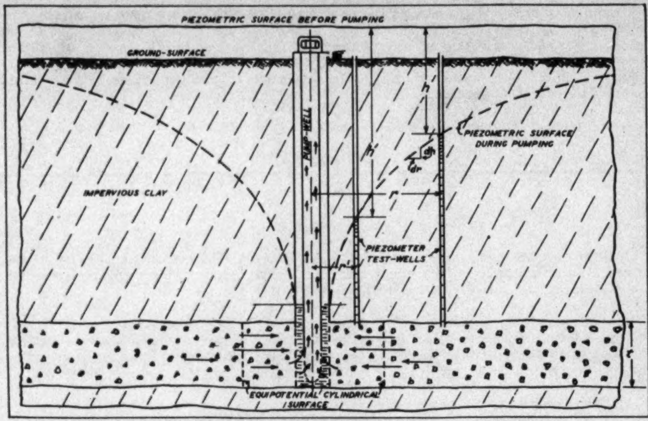
PIEZOMETRIC SURFACE BEFORE PUMPING
GROUND-SURFACE
PUMP-WELL
h
h'
PIEZOMETRIC SURFACE DURING PUMPING
dh
dr
IMPERVIOUS CLAY
r
PIEZOMETER TEST-WELLS
r'
t
EQUIPOTENTIAL CYLINDRICAL SURFACE

FIG. 1—SHOWING DIRECTION OF GROUND-WATER FLOW WHEN PUMPING AND THE MEANING OF SYMBOLS USED IN EQUATION (5)

The net area, a, of the cylindrical surface normal to flow and through which flow occurs is assumed to be

$$a = 2\pi r\ t\ f \qquad (b)$$

From the equation of continuity

$$q = a\ v = 2\pi r\ t\ f \times (kg/f)\ (dh/dr) \qquad (c)$$

From which

$$q\int_{r'}^{r}(dr/r) = 2\pi t\ k\ g\int_{h'}^{h} dh \qquad (d)$$

Integrating between the limits indicated, changing the logarithm to the base 10, and solving for the specific water-conductivity, k, it is found that

$$k = (2.303\ q/2\pi g)\ [\log\ (r/r')/t(h' - h)] \qquad (5)$$

In 1906 Thiem [3] derived the following equation which has been used recently for computing the coefficient of permeability

$$P = 527.7\ Q\ [\log\ (a'/a)/m(s - s_1)] \qquad (6)$$

Suffice it here to say, without defining all of the symbols in equation (6), that the quantities within the brackets in (5) and (6) are identical. Therefore, dividing (6) by (5) and remembering that Q of (6) is gallons per minute, and that q of (5) is cubic feet per second, it is found that

$$P = [(527.7\ Q \times 2\pi g)/2.303\ q]k = 2.08 \times 10^7\ (k) \qquad (7)$$

Thus the value of P in terms of k stated in equation (4) is verified.

Experimental procedure--A 14-inch pump-well near Logan, Utah, discharging 4.7 second-feet, and nine piezometer wells were used to evaluate k. The locations of six of the more distant wells are shown in Figures 2 and 3.

Figure 2 is a perspective view of the artesian aquifer and overlying clay and the wells.

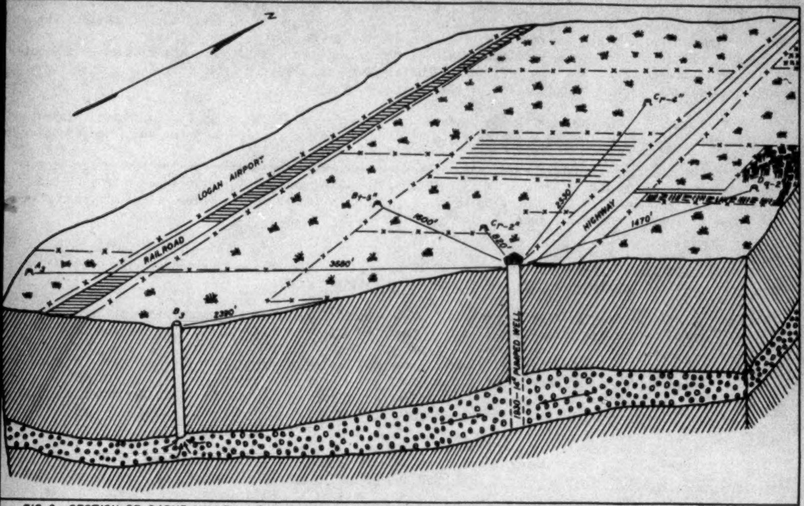
N
LOGAN AIRPORT
RAILROAD
HIGHWAY
A3
B3
Bt-5"
Cr-2"
Cr-4"
Dq-2"
3680'
2390'
1500'
820'
2330'
1470'
1930—14" PUMPED WELL

FIG. 2—SECTION OF CACHE VALLEY, UTAH, SHOWING ARTESIAN AQUIFER, LARGE PUMPED WELL, AND THE SIX SMALL TEST-WELLS AS USED FOR COLLECTING EXPERIMENTAL DATA

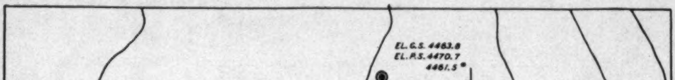
N
4460
4470
4480
4490
4500
EL. G.S. 4463.8
EL. P.S. 4470.7
4461.5 *
Cr-4"
2330'
EL. G.S. 4487.3
EL. P.S. 4492.9
4486.3 *
Dq-2"
1470'
EL. G.S. 4472.1
EL. P.S. 4472.8
4460.7 *
Cr-2"
820'
Bt-5"
1500'
EL. G.S. 4464.7
EL. P.S. 4471.1
4460.4 *
EL. G.S. 4453.1
EL. P.S. 4458.8
4454.6 *
A3
3680'
2390'
EL. G.S. 4462.5
EL. P.S. 4466.8
4458.9 *
B3
1930 PUMP-WELL
EL. G.S. 4477.6
EL. P.S. 4475.9
4417.2 *
G.S. = GROUND-SURFACE
P.S. = PIEZOMETRIC SURFACE
* ELEVATION OF P.S. AFTER 24 HOURS CONTINUOUS PUMPING

FIG. 3—PIEZOMETRIC-SURFACE CONTOUR-MAP OF VICINITY OF 1930 PUMP-WELL AND THE SIX PIEZOMETRIC TEST-WELLS, SEPTEMBER 1, 1932

The position, as well as the varying thickness or depth of the aquifer, is shown. The thickness of the aquifer varies from ten feet to 20 feet with an average of 15 feet, approximately. The stratum of clay overlying the aquifer has an average thickness of 40 to 50 feet. It is of importance to note that the perforated part of the casing of the 1930 pump-well extends to the bottom of the aquifer, thus contributing to radial flow when the pump is in operation. The piezometric wells merely reach the top of the aquifer as shown.

Figure 3 is a map showing the location of the representative piezometer-wells with respect to the 1930 pump-well; and also the slope of the piezometric surface when there was no pumping.

Observations--Readings were taken before the pump was started in order to obtain the elevation of the piezometric surface at assumed equilibrium. The pump was started at 8:16 a.m. and readings were made every 15 minutes thereafter for a period of 10-3/4 hours. (Data for the draw-down at the various wells were obtained on September 1 and those for the recovery on September 2, 1932.)

Assumptions--The use of equation (5) to compute the specific water-conductivity necessitates certain assumptions, the most important of which are:

(1) That the piezometric surface was in the same horizontal plane throughout the experimental field before the pump was started, or that the effect of the slope of this surface was negligible.
(2) That the thickness of the water-bearing stratum varies uniformly between the wells in which this thickness was measured.
(3) That the texture of the gravels is fairly uniform throughout the aquifer under consideration.
(4) That flow occurs radially from all directions toward the pump-well.

Results--The results of the specific water-conductivity measurements are presented in Table 1. It shows that three inner-radii (r') wells were used, namely: One having a radius less than one foot; one of radius nearly 16 feet; and one of radius nearly 63 feet. The draw-down at each of these wells was compared with the draw-down at each of six outer-radii (r) wells. The distances of the outer-radii wells from the pump in feet are 820, 1470, 1600, 2390, 2530, and 3680.

Table 1--Showing the specific water-conductivity, k, the pump-discharge, and lowering of the piezometric surface at different distances from the axis of the well (1930)
(Computed by formula $k = (Q/2\pi g\ell)\left\{[\ell n(r/r')]/(h-h')\right\}$)

Test-wells		Discharge of pump, second-feet	Outer radius, feet	Inner radius, feet	Drawdown of piezometric surface, feet		Specific water-conductivity
From	To	Q	r	r'	h	h'	k
1"	C_r-2"	4.7	820	0.916	30.23	12.08	5.9 x 10^{-4}
1"	D_q-2"	4.7	1470	0.916	30.23	6.63	4.9 x 10^{-4}
1"	B_t-5"	4.7	1600	0.916	30.23	10.67	6.0 x 10^{-4}
1"	B_3	4.7	2390	0.916	30.23	7.87	5.5 x 10^{-4}
1"	C_r-4"	4.7	2530	0.916	30.23	9.17	5.9 x 10^{-4}
1"	A_3	4.7	3680	0.916	30.23	4.17	5.0 x 10^{-4}
S-10	C_r-2"	4.7	820	15.58	24.91	12.08	5.0 x 10^{-4}
S-10	D_q-2"	4.7	1470	15.58	24.91	6.63	4.0 x 10^{-4}
S-10	B_t-5"	4.7	1600	15.58	24.91	10.67	5.2 x 10^{-4}
S-10	B_3	4.7	2390	15.58	24.91	7.87	4.7 x 10^{-4}
S-10	C_r-4"	4.7	2530	15.58	24.91	9.17	5.2 x 10^{-4}
S-10	A_3	4.7	3680	15.58	24.91	4.17	4.2 x 10^{-4}
N-10	C_r-2"	4.7	820	62.58	18.98	12.08	8.1 x 10^{-4}
N-10	D_q-2"	4.7	1470	62.58	18.98	6.63	4.1 x 10^{-4}
N-10	B_t-5"	4.7	1600	62.58	18.98	10.67	6.2 x 10^{-4}
N-10	B_3	4.7	2390	62.58	18.98	7.87	5.2 x 10^{-4}
N-10	C_r-4"	4.7	2530	62.58	18.98	9.17	6.0 x 10^{-4}
N-10	A_3	4.7	3680	62.58	18.98	4.17	4.4 x 10^{-4}

Table 2--Equivalent magnitudes of conductivity-factors

Specific water-conductivity	Transmission-constant	Coefficient of permeability
k	$k_s = 60\ g\ k$	$P = 2.08 \times 10^7 \times k$
5.9×10^{-4}	1.14	12.3×10^3
4.9×10^{-4}	0.94	10.2×10^3
6.0×10^{-4}	1.16	12.5×10^3
5.5×10^{-4}	1.06	11.4×10^3
5.9×10^{-4}	1.14	12.3×10^3
5.0×10^{-4}	0.97	10.4×10^3
5.0×10^{-4}	0.97	10.4×10^3
4.0×10^{-4}	0.77	8.3×10^3
5.2×10^{-4}	1.00	10.8×10^3
4.7×10^{-4}	0.91	9.8×10^3
5.2×10^{-4}	1.00	10.8×10^3
4.2×10^{-4}	0.81	8.7×10^3
8.1×10^{-4}	1.56	16.9×10^3
4.1×10^{-4}	0.79	8.5×10^3
6.2×10^{-4}	1.20	12.9×10^3
5.2×10^{-4}	1.00	10.8×10^3
6.0×10^{-4}	1.16	12.5×10^3
4.4×10^{-4}	0.85	9.2×10^3
Averages		
5.3×10^{-4}	1.02	11.1×10^3

The last column of Table 1 shows that the specific water-conductivity ranged from 4.0×10^{-4} to 8.1×10^{-4}, with an average for the 18 measurements of 5.3×10^{-4}.

Seven of the 18 measurements are within ten per cent of the average; seven range from 11 to 20 per cent; three from 21 to 30 per cent; and one exceeds the average by 50 per cent.

Equivalent magnitudes--Equivalent magnitudes of the specific water-conductivity, transmission-constant, and coefficient of permeability are shown in Table 2; all of these are based on the measurements reported in Table 1. It is evident that the average transmission-constant based on the Cache Valley studies is very nearly one, and the average coefficient of permeability is over 11,000.

Wenzel's measurements in Nebraska--Wenzel applied the equation of Thiem (eq. 6) for evaluating the coefficient of permeability, P, near Grand Island, Nebraska, in 1931. He made also a test near Kearney and one near Gothenburg, Nebraska, in 1933. His computed coefficients of permeability range as follows [4]:

Place	Coefficient P
Grand Island	919 - 1053
Kearney	4010 - 4290
Gothenburg	3750 - 3920

Is a new conductivity-factor needed?--It is appropriate to give thoughtful consideration to the need for a new term relating to permeability. The values of the widely used terms "transmission-constant" and "coefficient of permeability" are recognized and the fact that both were proposed by scientific men of outstanding merit is well known. However, certain needs exist, which it seems can be met by the introduction of a new term.

These needs and advantages may be summarized briefly as follows:

(1) The cubic foot per second (second-foot) is almost universally used as the unit of flow in hydraulics dealing with surface-flow and needs to be used for subsurface-flow.

(2) If the "second" is adopted as the time-unit in water-flow, then it is desirable to select a conductivity-factor having the physical dimensions of time. The specific water-conductivity, k, has the physical dimensions of time only. It has also the same numerical magnitude when measured in cubic centimeters per square centimeter per second as in cubic feet per square foot per second--thus making it readily adaptable to laboratory- and field-use.

(3) From an educational standpoint there is advantage in explicit use of the acceleration-constant, g, in the flow-equation.
(4) The use of a new conductivity-factor seems to be needed for and wholly consistent with the application of the potential, and the potential gradient--physical concepts of real value in the basic studies of soil-water movement.

The only evident disadvantage in the use of the term proposed--specific water-conductivity--is the fact that its numerical magnitude for nearly all soils is small. However, this may be largely overcome by the use of a term 10^{-x} as a factor in the number.

The term is presented with the hope that its merits, if any, may have the thoughtful consideration of those interested.

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PROSPECTING FOR WATER WITH GEOPHYSICAL METHODS

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Introduction

Prospecting for water is one of the most difficult problems of practical geophysics. It requires exceptional geologic ability on the part of the geophysicist, more than other applications of his science. Progress in this problem has been slow; from the commercial point of view, it is not particularly attractive; costs of geophysical water-prospecting frequently exceed those of surface geological surveys and approach expenses for drilling, particularly in small projects.

Definition of problem

In the ideal case, the geophysicist's task should be threefold: (1) Location of water; (2) determination of salinity; and (3) estimation of yield. With the present status of technique the geophysicist can rarely hope to predict yields unless he is working very close to wells reaching formations with known yields. In regard to determinations of salinity, approximate calculations can be made when working away from wells with water of known salinity, with electrical resistivity-methods. Excepting mineral and medicinal springs, water may be used for cattle with a salt content up to 0.7 per cent, while for drinking and culinary purposes the highest permissible [see 1 of references at end of paper] is 0.25 per cent. As the resistivity of the latter is around 180 ohm-cm [2] and that of the former about 65 ohm-cm, the resistivity of formations to be avoided on account of too low resistivities can be calculated. Assuming spherical grains in cubic arrangement, the resistivity ρ_x of a sand with the pore volume of "v" per cent may be obtained from the resistivity ρ of the water filling the pores: $\rho_x = 3\rho/v$ [2] so that for a porosity of 40 per cent a formation with a resistivity of lower than 1350 ohm-cm must be avoided when water is to be used for human needs, while for purposes of irrigation and watering stock, formations with resistivities down to 500 ohm-cm are tolerable.

Salinity-determinations being the exception rather than the rule, the geophysicist's task is narrowed down primarily to the location of water itself. Even this is not particularly easy; what the geophysicist can accomplish depends altogether on the amount of geologic information available and more specifically on the type of water and manner of occurrence.

Geophysical classification of underground water

For geophysical purposes, underground waters may be divided into a number of groups shown

TYPE OF WATER	RESERVOIR FORMED BY	METHOD OF LOCATION			
		STRUCTURAL	STRATIGRAPHIC		DIRECT
			Low Salinity	High Salinity	
(I) Ground	(A) Unconsolidated rocks (mostly alluvial) (1) Stratigraphic boundaries	See (3)	Resistivity	Resistivity Inductive Radio	Moisture-gradient (Rate of motion by salting and potential measurements)
			Seismic Acoustic Electric coring		
	(2) As in (1), with lateral confinement by impervious formations (faults, etc.)	Gravitational Magnetic Seismic Resistivity	Resistivity	Resistivity Inductive	
			Seismic Acoustic Electric coring		
	(3) Erosional boundaries (valleys, etc.)	Gravitational Magnetic Seismic Resistivity	See (1)		
	(B) Consolidated rocks (lime, igneous) (1) Horizontal porosity boundaries	See (3)	Resistivity	Resistivity Inductive Radio	Moisture-gradient
			Seismic Acoustic Electric coring		
	(2) As in (1), with lateral confinement (dikes, faults, etc., fracture-zones)	Gravitational Magnetic Seismic Resistivity	Resistivity	Resistivity Inductive	
			Seismic Electric coring		
	(3) Irregular surface of impervious rock	Gravitational Magnetic Seismic Resistivity	Resistivity	Resistivity Inductive	
			Seismic Electric coring		
(II) Fissure	Crevices, faults, fissures	Gravitational Magnetic Seismic Resistivity	See also (IB2)		Inductive Radio Radioactive Resistivity
(III) Cavern	Limestone, Dolomite, etc.		Resistivity	Resistivity Inductive Radio	Inductive Radio
	Rock-salt				Resistivity Inductive Radio
(IV) Mineral springs (thermal, saline, radioactive)					Geothermal Inductive Radioactive
(V) Pipe-leaks			(Resistivity)		Acoustic

FIG. 1—GEOLOGIC-GEOPHYSICAL CLASSIFICATION OF UNDERGROUND WATER AND OF GEOPHYSICAL LOCATION-METHODS

in Figure 1. First, the ground-water proper which is to include waters derived from precipitation and connate water; second and third, fissure- and cavern-water; fourth, spring water; and fifth, water issuing from leaks in water-pipes. The ground-water proper is subdivided into water occurring in unconsolidated and consolidated rocks, although this division arises more out of geologic than geophysical considerations, because the geophysical methods are very much the same in both cases. In each of the groups A and B under I, three subdivisions have been made classifying the water in these formations in respect to the geometric disposition of the reservoir as this determines largely type and procedure of geophysical surveying. The simplest case is the one of horizontal boundaries with the emphasis on the determination of the upper surface. The second manner of occurrence is similar to the first except that lateral circulation is blocked by impervious formations brought alongside the aquifer by faults, dikes, or fracture-zones. In the third type, the water occurs in troughs produced by erosional boundaries or surfaces of impervious rocks of other origin. Here the geophysical problem is not only one of determining the upper surface but frequently the lower erosional surface as well, or the latter alone if the upper surface is not determinable.

Definition of direct, stratigraphic, and structural location

The geophysicist has three ways at his disposal for the location of subsurface geologic bodies in the most general sense: (1) Direct location; (2) stratigraphic determination; and (3) structural mapping.

The first method of location is the exception rather than the rule in geophysical work, although definite substances like rock-salt, magnetite, sulphide ores, and radioactive substances may be definitely identified in suitable types of surveys by the experienced interpreter. Liquid and gaseous substances occurring as impregnations like oil, gas, and water, are particularly difficult to locate directly. It is obvious, however, that water occurring in form of thermal, saline, and radioactive springs may be located by temperature, electrical, and radioactive measurements; equally obvious is the direct location of water by its noise when escaping from pipe-leaks, and the determination of brine-accumulations in salt mines by electrical-resistivity, inductive, and radio-transmission observations. Water occurring in caves and fissures is on the borderline of direct and stratigraphic location as it is not always easy to decide whether the water as such gives the indication, or by virtue of an impregnated medium. Water filling large cavities in limestones or dolomites may be located directly by resistivity-measurements, or if sufficiently conductive, by inductive or radio methods; water which occupies fissures is often heavily mineralized and may thus be detected by inductive, resistivity, radioactive, and radio measurements. Direct applications of geophysics to the location of the ground-water table are limited to such special problems as the determination of the vertical moisture-gradient by hygrometric observations in different depths, and the calculation of the rate of motion of a ground-water stream in wells by salting the water and measuring the rate of motion of the surface potential-peak due to the lateral motion of the salt-water front [3].

The chief applications of geophysics to the location of underground water are of (1) a stratigraphic and (2) of a structural nature. As stated before, the resistivity of the impregnating water affects the resistivity of the rock in which it occurs; therefore, it is possible to distinguish a dry rock from a water-bearing rock under certain favorable circumstances. Water can thus be located by means of a local physical rock-classification based on differences in rock-conductivity. In analogy to the procedure employed in geology, this may be termed a "stratigraphic" method of water-location. Secondly, water may be located by attempting to find locations favorable for its occurrence; this involves the mapping of certain key-beds which may and may not be aquifers. The method is purely an indirect one, as structurally favorable points may not contain water owing to the absence of the petrographic requirements. This method, therefore, is called the "structural" method of locating water. Details of the latter will be discussed first and stratigraphic methods afterwards.

Methods of structural water-location

Referring to the tabulation of Figure 1, structural methods are applicable to the location of water confined by stratigraphic boundaries only if the aquifer or a conformable key-bed constitute some sort of a tectonic unit which is favorable to the accumulation of water. In this case the object of the structural investigation will be to locate synclines, troughs, and areas of general depression. Geophysically, this problem is so similar to that of mapping erosional troughs that the requisite geophysical methods have been tabulated under this heading. Passing on immediately to the latter, it is seen that virtually all major geophysical methods are applicable depending on whether differences in density, magnetism, elasticity, or conductivity occur on the erosional boundary. Thus, water-bearing gravel-channels and valley-fills may be mapped by the torsion-balance, by seismic methods, and by resistivity-methods of electrical prospecting. If the bottoms of the troughs or synclines consist of igneous or crystalline rocks, the magnetometer may be used for outlining their topography. For water-reservoirs confined laterally by faults, gravitational, seismic, and resistivity-methods are applicable; also magnetic methods, if the faulting has affected magnetic basement-rocks or if dikes of igneous origin cut through the water-bearing strata.

For structural investigations of consolidated water-bearing rocks, that is, occurrences of water in limestones, dolomites, and igneous rocks, the same geophysical methods apply provided sufficient differences exist in density, elasticity, and electric conductivity to map significant key-beds. For the location of crystalline rocks, faults, and dikes in connection with water-bearing limestones, dolomites, etc., the same considerations apply as discussed above.

In connection with fissure-water (see II of Figure 1), the function of structural geophysical work is the location of fissures or faults. Here gravitational, magnetic, seismic, and electrical methods apply depending on whether strata with differences in density, in magnetism, and in elastic or electric properties have been placed in juxtaposition by the faults.

Summing up, structural location of water is applicable as soon as the structural relation of the occurrence of water to detectable key-beds has been established, and such geophysical methods may be used which are employed in structural geophysical work for other purposes.

Methods of stratigraphic water-location

Contrarily to the methods of structural water-location, the aim of the stratigraphic methods is to determine condition and depth of the aquifer itself. Here, the choice of geophysical methods is much more limited. The increase in the density of a rock due to moisture is too small to be detected unambiguously by our present most sensitive gravity-instruments; moreover, the torsion-balance is a poor indicator of horizontal discontinuities. Moist and dry rocks do not differ in their magnetic properties. However, seismic methods are applicable under favorable circumstances as the elastic wave-velocity is greater in moist than in dry unconsolidated formations. Both the seismic refraction-method [4] and, under favorable circumstances, a binaural method of geophone-detection [5] are applicable. Although more expensive than electrical methods, seismic and acoustic methods deserve a great deal more attention than they receive at present as their possibilities are as great if not greater, particularly in giving additional safety in the interpretation of the results.

The application of electrical methods to the location of aquifers rests on the fact, mentioned before, that water in the pores of rocks will change their conductivity appreciably, so much that the conductivity of the mineral substance is virtually without effect. A formula was given at the outset for an approximate calculation. In practice, there are altogether four factors which determine the resistivity of formations, namely: (1) Porosity; (2) percentage of pores filled; (3) electrolytic conductivity of the water; and (4) duration of contact of the water with the rock.

The first two items do not require further explanation. The last two are intimately associated with one another, and item four depends on item one. When pure rain-water is stored in the pores of a formation, a certain amount of mineral matter will go into solution and change its electrolytic conductivity. The conductivity is increased the longer the water is in contact with the rock which, in turn, depends on the porosity (or rather permeability). Thus, fine-grained materials such as clays have much greater conductivities than coarse-grained sands or gravels. Moist clays have resistivities of about 0.5 to 1.5 kilo-ohms-cm while moist sands have from 5 to 20 kilo-ohms, showing the role played by capillary attraction and resulting stagnation.

The rate of motion of water through rocks is intimately associated with their conductivity. Medium-grained sands in which the water moves at a comparatively slow rate will generally exhibit an increased conductivity while coarse-grained sands or gravels, particularly those containing artesian water, will be very poor conductors; this type of formation is indicated later as "water-gravel" in Figure 4.

Contrasted with the conductivity discussed above which may be called "secondary conductivity" and which applies to formations infiltrated by water derived from precipitation, is the "primary conductivity" of formations containing "connate" waters which does not appear to be affected materially by the length of contact. These waters occur in the deeper sections of sedimentary formations and have been studied extensively in connection with oil-fields. The conductivity of formations filled with connate waters is exceedingly high, of the order of 0.1 to 0.4 kilo-ohms-cm [2]. Connate waters are generally not classed as ground-waters, are too saline for drinking and culinary purposes and occur at too great depths, although their location and depth-determination (down to some 1500 feet) is often a great deal easier than the location of near-surface ground-water [6].

Returning to the latter problem, it is seen that the electrical location of waters of secondary conductivity presents a twofold problem, depending on whether we deal with water of good or poor conductivity. This is indicated in the tabulation. Ground-water of low salinity can generally be detected successfully only by the application of some surface potential or resistivity-method, while waters of high salinities may be located not only by these methods, but in addition by inductive or radio methods. As the tabulation shows, this rule applies to all occurrences of ground-water, regardless of whether it occurs in unconsolidated or consolidated rocks, and whatever the form of the reservoir. Incidentally, high salinity does not necessarily mean that the water is unusable for domestic purposes. It is a matter of experience that very pure waters are much more difficult to locate than waters of fair conductivity, regardless of what method is applied.

It is readily seen that great difficulties must arise in the interpretation of electrical results from the fact that water-bearing strata may have both low and high conductivities, although a fair amount of help is derived from the observation that in the cases thus far investigated, ground-water of good conductivity (but usable) appears to be predominant over water of poor conductivity. However, even if it was the rule that water would result in increased conductivity, considerable difficulties would still exist. For, if in one location the addition of water reduced the resistivity of a dry sand from 100 to 20 kilo-ohms-cm, this same value could be possessed by a totally different formation, for instance, dry shale in another location. It is obviously impossible to recognize water by a specific value of rock-conductivity; in other words, the change in conductivity brought about by the presence of water is not great enough to produce really outstanding values of rock-conductivities. Here again the analogy with stratigraphic methods of geologic investigation applies; for it is not the absolute composition that is of value but the type of its variation with depth and its consistency in a horizontal direction, for purposes of correlation.

It is thus next to impossible to select any arbitrary location in virgin territory and to determine the presence and depth of water from the geophysical response. However, where the presence of an aquifer has been established in a well or from exposures, it is possible to correlate conductivities with water-bearing formations, their depth, type, and thickness, and to follow this type of indication into unknown territory until a complete change in character occurs.

It is also evident why, as stated at the outset, yield-determinations from electrical results are generally impossible. While the increase in conductivity in a sand can as a rule be taken as an indication of the presence of water, the indication resulting from it may be confused very readily with that from a moist clay which does not yield water.

Summing up, stratigraphic location of water by electrical geophysical methods has practically all the odds against it; saline waters are easy to locate, but the better the indication, the less usable they are; moist beds of low yield are likely to give better indications than water-gravels of high yield; finally, beds with the best type of water give indications which are most readily confused with those from formations which are not water-bearing.

Instruments for water-location

From the following discussion, the divining rod and all other devices which belong in that class will be excluded. It may be perfectly possible that certain persons of supernormal faculties can sense the presence of water, but this is something to be discussed by a psychologist and not by a geophysicist. Besides, if the numerous, wiggle-stick and doodle-bug men who pretend to be able to locate water possessed such faculty, there would be no need for them to employ any of their mysterious devices. There is an instrument called the "Mansfield water-finder" [8], which consists of a magnetic needle in a coil of iron wire with about 5000 turns; the needle is supposed to start oscillating above subsurface water-courses. It is difficult to state a physical principle to account for the action of this device; to the author's knowledge, there is no reference in the literature to any actual tests made with the apparatus on known geologic or hydrologic conditions; it appears exceedingly doubtful whether the instrument can do what is claimed for it.

For the direct location of water, the geothermal, radioactive, inductive, and radio methods were mentioned. For details on these, the reader is likewise referred to the text-books and literature; ample references are given, for instance, in Ambronn's book [9]. Inductive methods of electrical prospecting utilize an insulated cable or loop to energize conductive beds whose magnetic field may be picked up by search-coils at the surface and surveyed in reference to phase and amplitude. Details about this method may be found in various books and articles [10, 6]. Radio methods differ from inductive methods by the use of a much higher frequency; the radiation from the transmitter is propagated in poor conductors and reflected from good conductors. Their application is limited by the high rate of absorption in surface-formations in temperate climates but appears to be more promising for water-search in arid regions [see 9, results]. Details on methods and results may be obtained from articles by Petrowsky [11] and Fritsch [12].

In reference to structural water-location, it was stated before that virtually any of the major geophysical methods may be used when a definite relation between structure and occurrence of water has been established. However, practical consideration will limit the application of some of them. For instance, the torsion-balance is slow, limited by rugged topography, and too expensive compared with the electrical and seismic methods. Applications of the magnetometer are rare and indications at times too indefinite, although it has the merit of speed and inexpensive operation. Instruments for gravimetric and magnetic prospecting will, therefore, not be described here; discussions of principles and operations may be found in most geophysical textbooks. For structural work, seismic and electrical methods are foremost in speed and definiteness of interpretation. The same is true for stratigraphic water-location.

Of the seismic and electrical methods, the seismic refraction and the electrical surface-potential (resistivity, potential ratio, and potential gradient) are the ones in chief use at present. Before going into details of these, a number of other seismic and electrical methods now in less frequent use for location of water may be mentioned.

Two electrical methods which aim to accomplish similar results as now obtained by the resistivity-method are the electromagnetic method of Haalck [13] and the ring-induction method of Koenigsberger [14]. In the former, an alternating-current generator is grounded at two points; the spacing between them is varied as in the resistivity-method, the depth-penetration being approximately one-third of the electrode-interval. Between the two electrodes an induction-frame is set up, with plane vertical and parallel to the electrode basis. As the current from the electrodes traverses strata of differing conductivities and different depths the electromagnetic field changes and with it the inclination of the induction frame for zero-induction. The tilt-angles of the frame are plotted against electrode-separation; breaks in the curve so obtained are assumed to correspond to vertical changes in conductivity (formation-boundaries). In Koenigsberger's central induction-method, current is supplied to the ground inductively by a ring-shaped loop whose diameter is increased step by step to obtain increased depth-penetration. The secondary field is picked up by a horizontal induction-coil and measured in respect to phase and amplitude. The apparent resistivity can be calculated from the secondary field and is plotted against radius of the induction-loop. Application of this method for problems involving depths less than 150 feet is not recommended by the author.

An electrical method which is sometimes useful in establishing actual resistivities in a water-bearing section and in extending resistivity-measurements into unknown territory from wells, is the electrical coring-method of Schlumberger [15]. However, it has to be applied in water-wells before they are cased.

In the seismic field, methods which have been applied occasionally and show promise for the future are the acoustic or geophone method, and the reflection-method. The geophone is an instrument constructed like a stethoscope and used for the detection of sound by ear. It is applied chiefly for locating water-leaks from pipes by the noise of the water impinging on surrounding gravel, etc. For ground-water location, two phones may be used connected through a compensator to determine the direction of sound as reflected from the water-bearing strata [16]. Reflection-methods based on travel-time observations with seismic detectors have found extensive application in the oil-fields but have been barred from civil engineering and ground-water applications because of the difficulty of eliminating interference of shallow reflections with the first refraction impulses. However, a solution of this problem is very probable in the course of the next two years.

The methods used chiefly at this time for the location of ground-water are the seismic-refraction and the electrical-resistivity (and or potential) methods.

A seismic-refraction equipment may be used for the purpose at hand in two ways: With or without amplifiers between detector and recording galvanometer. The insertion of the latter gives far greater sensitivity but calls for more equipment. The function of the detector (pick-up, seismograph, geophone) is to convert the mechanical ground-vibration into electrical impulses. This can be done in various ways: First, by adaptation of the carbon-microphone principle (not recommended, on account of the high noise-level); secondly, by the use of a condensor-microphone; third, by using an inductive seismograph (adaptation of the dynamic-speaker principle); and fourth, by a reluctance-seismograph (a reversed magnetic speaker, for instance, of the Baldwin type). The last two types are in predominant use. The vibration-detectors may be connected to intermediate amplifiers, depending on the sensitivity required. From the amplifiers or from the detectors directly, the impulses are transferred to a recording galvanometer of the coil, string, or oscillograph loop-type. In refraction-work a much higher sensitivity than that of the customary oscillograph is required, of the order of 0.1-mm deflection per microampere. The galvanometer-deflections are photographed on rapidly moving paper in a recording field-camera. Time-marks at intervals of 1/100 of a second are provided on the record and likewise the instant of the shot is transferred to the record electrically. Details of this equipment may be found in one of the author's recent articles [4]. Generally, six detectors, six amplifiers, and six galvanometers are used, but time can be saved both in the field and in the evaluation of the records by using 12 channels. After the shot has been fired and records have been obtained in six or 12 distances, respectively, the times elapsed between the instant of the shot and the first arrivals are taken from the record and are plotted as travel-time curves from which depths of boundaries of formations and elastic-wave speeds within them may be calculated.

In the electrical resistivity-method, generally four electrodes are driven into the ground and the external pair is connected to batteries and an ammeter. The current passing through the ground is measured; the potential difference set up between the internal pair is observed on a potentiometer or voltmeter. The ratio of current and voltage, multiplied by a factor depending on the spacing of the four electrodes, gives the apparent resistivity. The method may be used in two ways. In resistivity "sounding," that is, in the determination of the vertical variation of resistivity at one point, the electrode-interval is increased in steps. As the depth-penetration is approximately equal to the electrode-interval, the apparent resistivity is plotted against electrode-spacing, the curve thus obtained is rotated 90°, and thus a diagram is obtained which gives the apparent resistivity as function of equivalent depth (see Fig. 2). Theory [see 7] and practice show that no sharp breaks are obtained at formation-boundaries with this method; as a matter of fact, depth-calculations are somewhat involved. When the problem is one of determining relative depth of a given horizon (water-horizon, bed-rock) in an area, another process is applied called "resistivity-mapping." In this process, the electrode-separation is adjusted to a large enough value to penetrate below the horizon to be mapped and is kept constant; locations in the area to be explored are occupied with this arrangement whereby apparent resistivity-contours may be drawn which represent approximately the changes in depth of the key-beds.

Two variants of the resistivity-method are the potential-drop-ratio method [17] and the potential-gradient method (Heiland). The purpose of both is to improve the depth-indications

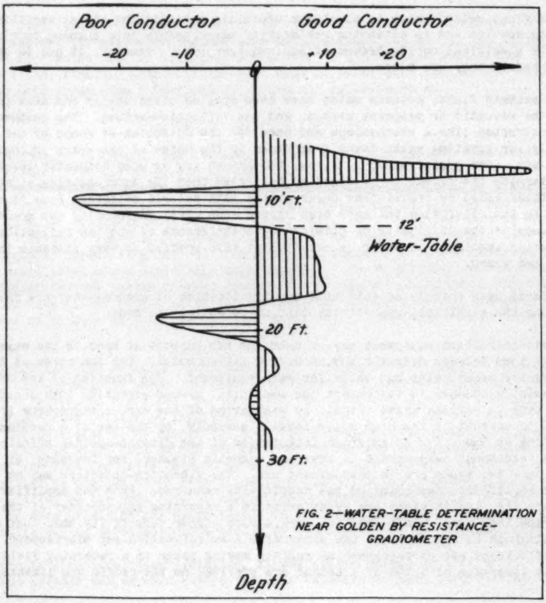

FIG. 2—WATER-TABLE DETERMINATION NEAR GOLDEN BY RESISTANCE-GRADIOMETER

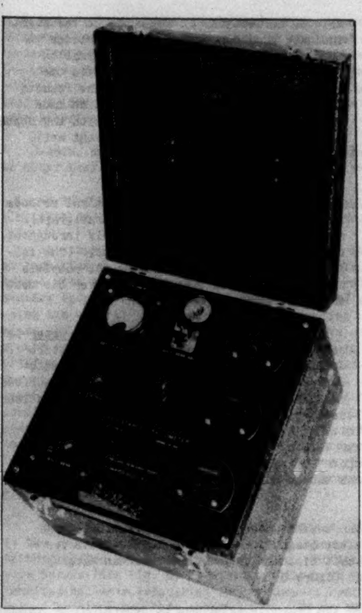

FIG. 3—RESISTANCE-GRADIOMETER FOR DIRECT DEPTH-DETERMINATIONS

obtained with the resistivity-method. In the potential-drop-ratio method two electrodes are grounded far apart and connected to a 500-cycle generator. Measurements are made in the vicinity of one power-electrode with an alternating-current-bridge arrangement which is grounded at three points and makes possible the determination of the ratio of the potentials along the two intervals formed by the three electrodes. This ratio is measured on traverses radiating out from the power-electrode or along a traverse at right-angles to the electrode-basis and plotted as function of the distance of the center secondary electrode from the power-electrode. These horizontal distances are multiplied by a factor and the diagram rotated 90°; then, formation-boundaries will appear as peaks in the curve; a peak to the right means a change from a good to a poor conductor and a peak on the left a change from a poor to a good conductor.

In the resistance-gradient method a higher derivative of the surface-potential function is measured in such manner that the depth to formation-boundaries are read directly from the instrument without conversion. An instrument suitable for this purpose is shown in Figure 3. It consists of an alternating-current direct-reading bridge with a highly sensitive galvanometer as zero-instrument. Low instead of high frequency is used to increase the depth-penetration which eliminates the necessity for phase-determinations. Measurements are again made near one of the power-electrodes; readings are plotted, the diagram is rotated 90°, and a curve is obtained as shown in Figure 2. The measurements shown in Figure 2 were made to determine the depth to water-table. In this

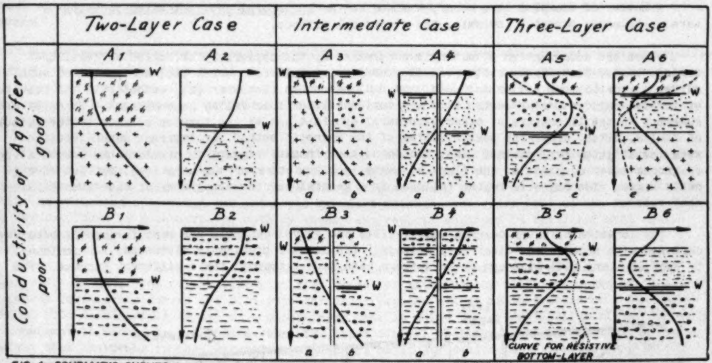
Two-Layer Case
Intermediate Case
Three-Layer Case
Conductivity of Aquifer
good
poor
A1
A2
A3
A4
A5
A6
B1
B2
B3
B4
B5
B6
W
a
b
e
CURVE FOR RESISTIVE BOTTOM-LAYER

FIG. 4—SCHEMATIC CURVES SHOWING APPARENT RESISTIVITY-INDICATIONS OF CONDUCTIVE AND RESISTIVE AQUIFERS

LEGEND
DRY SURFACE-FORMATION
MOIST SURFACE
WET SANDS
DRY SANDS
WATER-GRAVELS
DRY GRAVELS
MOIST CLAY
GRANITE
a|=TWO LAYERS
||b=THREE LAYERS
e=EXTREMES
W=WATER

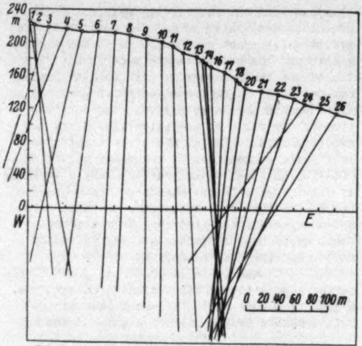

FIG. 5—ELECTROMAGNETIC TILT-ANGLE SURVEY ON SUBTERRANEAN WATER-COURSES, KARST COUNTRY, NEAR FIUME (AFTER REICH)

method, deflections of the curve to the right indicate good conductors and deflections to the left poor conductors, while formation-boundaries show as intersections with the depth-ordinate. It is seen from the results obtained that the depth-determination made with this instrument agreed well with the depth to water as determined in an adjacent well.

Discussion of results

Results obtained with geophysical methods in the direct, structural, and stratigraphic water-location are scattered widely throughout the literature in various languages. The following discussion of results is not complete but an attempt has been made to cover the most important and most significant data.

As far as the direct location of water is concerned, most of the available literature deals with fissure- and fault-water. Radioactive reactions above them have been described by Ebert [18] and Ludewig [19]. Such reactions are distinct only when the overburden is thin. Ludewig's objective was the location of radioactive waters of medicinal importance in the vicinity of a spa. Highly conductive water on faults and fissures can generally be located rather well by high-frequency inductive methods. Cloos [20] could detect their presence by "dead-spots" in radio reception. However, there is some doubt as to whether some of these observations should not more properly belong into the group of structural location of water.

Attempts have been made to locate subterranean cavern-water by radio observations [12]. Good results may also be obtained by the use of electromagnetic methods using 500-cycle frequency, as demonstrated by a survey of reception-coil tilt-angles over subterranean water-courses, published by Reich [21] and reproduced in Figure 5.

Finally, Koenigsberger [22] has discussed how the depth to water can be determined by measuring relative humidities in shallow holes.

A number of examples have been published on the structural indirect water-location by torsion-balance, magnetic, seismic, and electrical methods.

Where the accumulation of water is controlled by the topography of buried valleys, the surface of bed-rock may be contoured with the torsion-balance. Holst [23] has published such a survey of the Dreisam Valley in Baden; and McClintock and Phemister [24] demonstrate the results of torsion-balance measurements above the buried Kelvin River Valley near Glasgow. Examples are numerous in the literature of other structural applications of the torsion-balance to the location of faults, dikes, etc. The possibilities of the magnetic method for indirect water-location were investigated by Grohskopf [25], who found that in many regions in Missouri the accumulations of ground-water occurred at the flank of magnetic highs and near magnetic lows, but not on magnetic highs. The magnetic relief followed in a general way the topography of the igneous basement-rocks.

The location of water-bearing valley-fills and gravel-channels has most frequently been undertaken with seismic and electrical methods. The seismic problem is discussed, for instance, by Edge and Laby [10] although their surveys were made primarily for a different purpose. The

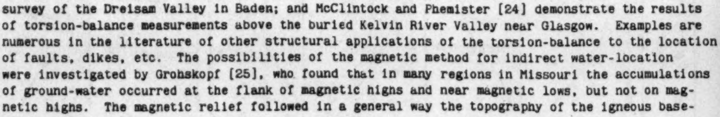

FIG. 6—REFRACTION TRAVEL-TIME CURVES ON GROUNDWATER-LEVEL (ADAPTED FROM RIEBER)

same authors have applied resistivity-measurements to the location of such channels. Frequent reference is made in the literature to the location of sand- and gravel-lenses in clays by resistivity-measurements [26, 27, 28]; the problem becomes one of structural water-location if the sands, as is often the case, are water-bearing. De Ceccaty [3] has published a resistivity-survey of a valley filled with water-bearing alluvial beds above impervious cretaceous marls, in Algiers, and one of the topography of impervious nummulite chalk under water-bearing Quarternary near Biarritz.

Again, where faults [29], dikes, or fracture zones [30] are associated with the occurrence of water they may likewise be located by resistivity and seismic measurements.

As to stratigraphic methods of water-location, results obtained with methods other than resistivity or potential-drop methods will be discussed first.

As stated before, waters of high salinity may be located with comparative ease by the use of inductive methods. Sundberg [31] and Zuschlag [6] have published in detail the results obtained with their inductive methods in structural studies by using the high salinity of sedimentary beds in oil-fields. Koenigsberger [14] gives an example of the reaction obtained by using his central induction-method on a section with water-bearing gravels above conductive clays and marls. Loewy and Leimbach [32] have described the determination of the distance of a ground-water level from below by measurements in the interior of a salt-mine, and have given a brief summary of the applications of their radio-interference method of ground-water location in desert regions of Southwest Africa. Stern [33] discusses the application of reflection of radio waves from a water-surface in a quarry, but points out also that their depth-penetration is exceedingly limited; for a wave-length of about 50 meters, the penetration for fairly dry limestones and sandstones is from 30 to 70 meters while for clay it would only be about eight meters. Hence, the usefulness of radio methods for ground-water locations in temperate and moist climates is doubtful. With his electromagnetic method, Haalck [13] tested deposits of lignite in Germany and found distinct changes in the electromagnetic field depending on the change of water-content of the deposits with depth.

A number of examples have been published showing the possibilities of the seismic methods in the location of water-bearing strata. The increase in velocity due to water-saturation of unconsolidated sediments is appreciable. Heiland [4] illustrates this with a number of travel-time curves (see Fig. 6) obtained by Rieber in California on shallow-water sands. While the longitudinal-wave velocities in dry loose formations seldom exceed 2000 feet per second, these same formations may show speeds up to 4500 to 6000 feet per second when saturated with water. De Ceccaty [3] has published travel-time curves obtained in the location of a Cretaceous chalk with artesian water-supply in South Tunis, and has reproduced reflection-seismograms obtained in the study of artesian horizons, likewise in Tunis, with reflecting beds at depth of 350 and 800 meters.

By far the majority of ground-water studies have been made with the electric resistivity-method. Results of various types obtained in all parts of the world by different authors will be discussed. A study of this and of a great deal of unpublished material has resulted in working out a definite scheme of indications which has proved to be helpful in arriving at better interpretations.

This scheme is shown in Figure 4. Most curves were obtained from field-data but were simplified for Figure 4. Apparent resistivities are plotted to the right, electrode-separation and thus depth downward. In no case are there sharp breaks (sharp breaks on boundaries are obtained with the potential-drop-ratio and potential-gradient methods, see under [8]) on the formation-boundaries; this is substantiated both by theory and results obtained in the field with equipment of good construction.

The case of two layers is illustrated by two curves on the left, that of the three-layer case on the right. Two curves have also been drawn for intermediate cases, so named because the apparent resistivity-curves are of a type which corresponds either to an extreme of a two-layer set-up with thin surface-layer, or a three-layer case in which the conductivities either increase or decrease in three steps downward, that is, types similar to those shown on the extreme right except that the peaks in the intermediate layer are no longer noticeable. The two-layer section is shown in the "a" part of these four curves and three-layer section in the "b" part. In the three-layer case, strata of different conductivities are interbedded between a surface and a bottom-layer whose conductivities are similar. Curves of same appearance have been arranged below one another to show the difference in interpretation between the curves obtained when the aquifer is a good conductor and those when it is a poor conductor [7].

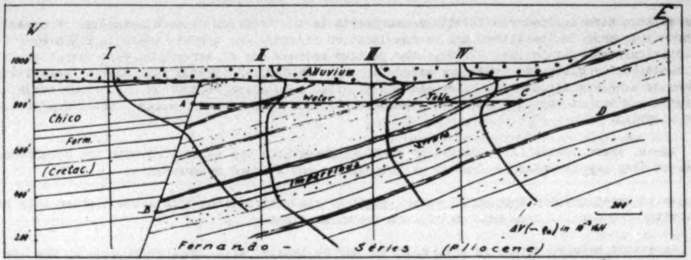

FIG. 7—APPARENT RESISTIVITY-DEPTH CURVES IN SAN FERNANDO VALLEY, CALIFORNIA (ADAPTED FROM J. J. JAKOSKY)
[3-LAYER CASE, WATER (GOOD CONDUCTOR)= BOTTOM LAYER, WATER-LEVEL BELOW PEAK; CONDUCTIVE WATER IN TRIANGLE ABC]

As indicated before, the practical examples where the aquifer was a poor conductor are less numerous than the ones where it was a good conductor; this will help some in the practical applications of the diagrams. The two-layer curves are less frequent in practice than the three-layer curves; of the former, A1 is most frequent, A2 ranks next, then follows B2 and last B1. The three-layer group is observed more often than the intermediate group. It is difficult to give curves in this latter group different ranks; probably A3 is the most frequent.

As to the three-layer group, the curve A5 is far the most predominant, not only in this particular group, but may be called the water-indication found frequently in widely different areas. Type A6 follows after that. Of the B-type curves, B5 comes probably first and B6 last.

It was stated above that the majority of water-indications obtained with the 4-terminal resistivity-method follow the type A5, with A6 a close second. Results conforming to the former will be discussed first. The type-A5 indication is obtained when the ground-water occurs in sand and gravels and thus makes their lower portion more conductive, while the dry portion above remains a poor conductor. The surface evaporation-zone is the top conductive layer in this combination. The ground-water level in virtually all of these curves occurs slightly below the peak. This was probably first observed by W. J. Rooney [34] in the copper country of Michigan for a water-level some 25 feet deep in glacial drift, above Keweenaw rocks at depth about 70 feet. Some of his curves show a rise instead of the drop below W in type A5. At Huancayo [35] he obtained typical water-curves in alluvial deposits, and states that wells dug in the general area in search for water did not find it (possibly the wells were not deep enough; the curves indicated low resistivity-level at depth about 80 feet). In 1930, Jakosky [36] conducted surveys in the San Fernando Valley in California and obtained a series of good ground-water indications of the same type (Fig. 7). In the following years, extensive ground-water studies were made at the Colorado School of Mines; a number of typical ground-water curves obtained mostly by Tattam were published by him [37] and Heiland [30] from Colorado, New Mexico, and Texas, and similar curves were contributed by Henderson from California. Tattam [38] continued his studies in Nigeria; in virtually all localities where usable curves could be obtained, they were of

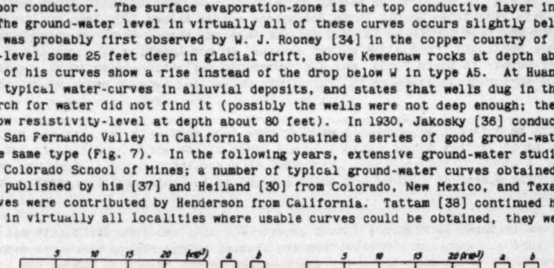

FIG. 8—WATER CURVES IN KARST COUNTRY (AFTER STERN)
[3-LAYER CASE, WATER (GOOD CONDUCTOR)=SECOND LAYER, WATER-LEVEL ABOVE PEAK (OR TROUGH)]

the type A5. Depth-determinations were made on the basis of these curves whenever possible, and in some cases the geophysical predictions were checked by later water-wells. For water-bearing gravels underlain by clays in 60-foot depth, Koenigsberger [14] obtained a distinct curve of the same type near Freiburg, Germany. Dry sands above water-logged deposits of lignite produced the typical water-curve in the Rhenan Lignite Area of Ville [39]. Curves obtained by Hawkins [49] on Ontario lignite-deposits show almost an identical character, probably for the same reason of water-logging. Virtually all curves published by Stern for the Ville Area are identical, while similar geologic conditions in the Niederlausitz Lignite districts showed curves which are difficult to fit to any of the simple schemes of Figure 2, because of more frequent alteration of good and poor conductors. Near Cologne, sands above the lignite were water-bearing at the bottom, producing a curve similar to A5 with very low resistivities on the lowest part of the curves corresponding to the water-logged lignite.

Tagg [40] obtained a curve of the A5-type near Cheltenham, Gloucestershire, on a limestone underlain by sand at one location, while at another the curve completely reversed itself and, for the same surface-formation, became the A6-type. The interpretation was that in the first case the lime was underlain by sand taking up the moisture filtered through the lime, while in the second case clay was assumed to exist which kept the moisture in the lower portion of the lime.

In a technical memorandum published by the manufacturers of the "Megger" resistivity-instrument, Tagg [41] presents a typical ground-water curve obtained in England and demonstrates how the depth to the water-level is calculated.

In the Hawaiian Islands, a layer of fresh water "floats" on salt water in porous lava; this condition gives rise to a three-layer curve of the A5-type (except at the immediate surface) with the salt water corresponding to the lowest layer. The top of the salt water is thus located below the peak in the curve and its depth can be determined. Swartz [53] claims very accurate depth-predictions could be made from microscopic breaks in the curve. The reality of such breaks is still doubtful, in the opinion of many authors. Confirmation of predictions based on these by drilling is no proof for their existence. By geologic inference based on the attitude of beds in a well-known area, interfaces can be predicted even at depths where the resistivity-curve shows no indication, as long as geologically related interfaces have been indicated at other points of the curve.

The second type of typical water-indication, A6, is obtained when water-bearing sands, gravels, valley-fills or wash, rest on impervious formations of high resistivity, such as limestones, granites, etc. Then the upper layer is generally not altogether filled with water; this results in its being split up into a dry and poorly conductive surface-layer and a moist and conductive intermediate layer. In this case, the low-resistivity peak corresponds with the water-bearing beds with the water-level above the peak; the curve is the reflected form of A5. Frequently, the extreme form "e" (see Fig. 8) is observed. Contrarily to statements by some authors, this does not imply that the bottom-layer is of low resistivity; in fact, Poldini [43] calculated that this curve may be obtained for infinite bottom-layer resistivity if the conductivity of the intermediate layer is great enough (saline waters). This regular A6-type of water-indication was obtained as early as 1925 by Gish and Rooney [42] in the Bradley Hills, Maryland, for Pleistocene strata about 100 feet thick on crystalline bed-rock. The extreme "e" curve was obtained by Gish at College Park, Maryland (water-bearing Pleistocene on granite), Washington (filled ravine), and near Watheroo, Australia. Rooney [34] found the same for water in the low portion of overburden above Keweenaw formation in Michigan. Distance of this overburden from a mine-stope below was then also determined. In this problem, the sequence of formations and hence the curve was reversed (as in A5). In the many investigations carried out by Schlumberger and his collaborators for the determination of depth to bed-rock, conductive water-bearing portions in glacial drift above crystalline rocks have been frequently encountered and gave rise to the typical A6-curve, as for instance in the survey published by Crosby and Leonardon [44] for a New England dam-site. Likewise, Jakosky and Wilson [45] in a water-survey in the Santa Rita Mountains, Arizona, obtained the same curve for fill saturated at the bottom, above bed-rock, and under similar conditions in Trinity County, California. The Cypress sandstone above the Mammoth Cave limestone produced, where water-bearing, a distinct drop in resistivity, as determined by Eve et al [46]. A distinct drop in resistivity was found due to water collecting above asphalt-sands near Bowling Green, Kentucky, giving rise to a curve similar to A6 in its near-surface portion [46]. Possibly in the same class belong the results obtained by Schlumberger on salt domes in Alsace, where highly conductive clays and marls, possibly impregnated with saline waters, overlie poorly conductive sands and resistant salt [43]. Extensive studies were made of the relation of ground-water and apparent resistivities by Loehnberg and Stern [47]. The section consisted of gravels on top, sands and marls below, and limestones at the bottom. Water is con-

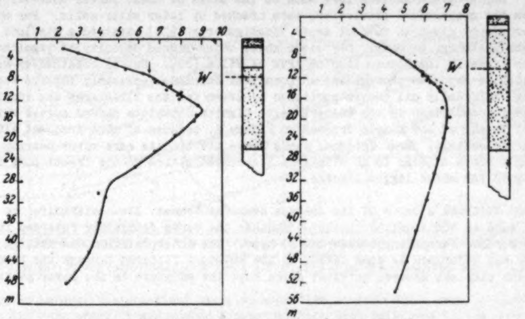

FIG. 9—WATER CURVE NEAR COLOGNE (AFTER STERN)
[3-LAYER CASE, WATER (POOR CONDUCTOR) = SECOND LAYER, WATER-LEVEL ABOVE PEAK]

tained in the marls immediately below the sands, and in crevices and caverns near the top of the limestones. Here, in many cases, the extreme A6 "e" curves were obtained, with drops for the near-surface water and gradual rise in the limestones below, interrupted by low resistivity-drops for the cavern-waters. In the absence of the high-resistivity surface-peak these curves sometimes degenerated into the A3-type (see Fig. 8).

Next in the order of this discussion are water-indications corresponding to the other A-types. To begin with A1, this type has been encountered by Schlumberger and others in his foundation-investigations [see 44] although they do not state specifically that the top layers were water-bearing. A2 is rather rare as this type is likely to occur more in the three-layer form of A5. More examples are available for the A3-type which is obtained when water occurs near the surface and highly resistant media below. It is similar to A1 and A6. Numerous curves of this type were obtained by Stern and Loehnberg [47]. The same curves were observed by Edge and Laby [10] for sands and clays above coral when filled with water of low salinity (therefore, possibly belonging into the B3-type); for the identical section, however, the curves changed to the opposite A4- and A5-types when the waters were saline. Some of the curves published by Stern [39] for the Niederlausitz Lignite deposits possibly belong in the A3-class as they start out with low resistivities for the moist surface-sands, then gradually increase for the moist lignite and reach their highest value for the footwall-sands which are probably dry.

As far as the indications of poorly conductive waters are concerned, results published are exceedingly scarce. This is probably due to the fact that this type of indication is difficult to obtain and readily confused with the A-type; furthermore, dry gravels and moist gravels saturated with water of good conductivity are not readily distinguished. However, what little has been published is definite enough. Hubbert [27] by resistivity-mapping, could definitely establish indications from water-bearing gravels may be indicated by high-resistivity values. Kelly reports having mistaken a deeply buried gravel-deposit in a dam-site investigation for bed-rock, no doubt on account of the purity of the water contained in them. That this is readily possible may be verified by a comparison of type A1 with B1. Water-indications of the B5-type have been obtained by Rothrock [48] in a South Dakota water-survey, where conductive glacial clays occurred at the top, water-gravels below, and resistive shales at the bottom. (In the B5-type of Fig. 4, the clays are assumed to be conductive; Rothrock's indications, therefore, approach the B3,a-type.)

In surveys made by Lee [52] in Nevada deserts, water-bearing gravels appeared as high-resistivity indications, the type-indication approaching B3,a. In the Tidal Basin of the Potomac, Gish [42] carried out some "model" experiments with (river) water on top, mud below, and hard rock at the bottom, and obtained a curve of the type B6 (with bed-rock in place of W) which originates from B2 by addition of a third resistive bottom-layer.

Most definite about the highly resistant nature of water-bearing gravel are Stern's [39] measurements near the bight of Cologne. The curves obtained there are typical water-curves, but their interpretation is not that of A5, but of B5, as the water does not occur below the peak but above the peak. This was verified by a comparison of the resistivity-results with wells (see Fig. 9).

Contamination of fresh-water supplies by saline waters may be detected, and boundary-lines between fresh and saline waters may be established by locating points where changes in type-curves occur. If the fresh water is non-conductive, changes in salinity should result in changes from the B5- to the A6-curve, or from the B6- to the A5-curve. If the fresh water is conductive, changes in salinity will result in extreme A5-curves corresponding to very high bottom-layer conductivity. Near El Paso [A. N. Sayre, written communication; Swartz, 43], the A5-curve was found to change to the A6-curve with an increase in salinity; fresh water occurring some 200 feet below the surface under the mesas, saline waters at depth of 80 to 100 feet below the Rio Grande Valley.

Owing to the fact that the potential-drop-ratio methods are of comparatively recent date, very little has been published on results obtained with them, although they merit much greater attention for water-search than they have received thus far. Cox [50] attempted to locate water-flooded portions of mine-workings by ratio mapping at the surface, but found that the indications were overshadowed by surface-resistivity variations caused by outcrops of different beds to such an extent that it was not possible to determine definitely the boundaries of the flooded areas. Probably in most cases the flooded areas were much too small in comparison with their depths, being 200 to 300 feet in one case and 700 feet in another. Only in a third location, where the depth was around 60 feet, fairly promising indications could be obtained.

A survey indicative of the possibilities of the potential-ratio methods has been published by Lundberg and Zuschlag [17]. In an area where arkose bed-rock was overlain by glacial drift, the lower portion of which was water-bearing, the water-level was clearly indicated by peaks to the left in the potential-ratio-depth curve. Thus, the water-table depth was indicated much more distinctly than by resistivity-measurements; in that case, curve A6 would have been obtained.

Economic aspects of geophysical water-location

The foregoing discussion of results obtained with various types of geophysical methods in the direct, structural, and stratigraphic water-location brings out most impressively that a geophysical water-survey is doomed to failure unless undertaken by some one well versed in the geologic possibilities of the occurrence of water. As it is, a geophysical survey is expensive, and its cost is comparable with that of drilling shallow wells or having an expert geologist examine the prospect. Therefore, it is doubtful whether geophysical methods are economical for the location of a single or even a few wells. Only if the project is large enough, a geophysical survey of such proportions as to acquaint the operator with all geological and geophysical possibilities appears to be warranted. When undertaken, the closest cooperation between geophysicists and geologists acquainted with the area is necessary, and, if possible, the opinions of hydrologists and climatologists should be consulted. Unless surveys of this type can be undertaken on a cooperative basis with scientific institutions, the applications of the more expensive methods such as torsion-balance are generally not economical. Next in expense are seismic methods, which when properly handled are likely to give results equivalent or superior to those obtained with resistivity-methods in interpretability. In most cases, the choice will be the resistivity-method, but, owing to the superiority in depth-determinations from field-data without elaborate calculations, also the potential-drop or gradient methods are likely to attain a definite place in electrical water-search.

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APPARATUS FOR STUDYING WATER-RELATIONS IN POTTED PLANTS

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(Contribution from the Iowa Agricultural Experiment Station, Journal Paper No. J475, Project 487, in cooperation with the Physics Dept., Iowa State College, Ames, Iowa)

The apparatus here described was developed to obtain information on the flow and distribution of water in soil as effected by the moisture-absorption of plant-roots. It was desired also to obtain information on the operating characteristics of double-walled irrigators which were developed for the purpose of securing automatic control of soil-moisture for potted plants.

Apparatus and experimental procedure--The essential details of the apparatus are shown in Figure 1. The irrigator-pot was suspended from a scale-beam and a pen attached to an extension of the beam was used to give a continuous record of the weight of pot. The 200-pound capacity

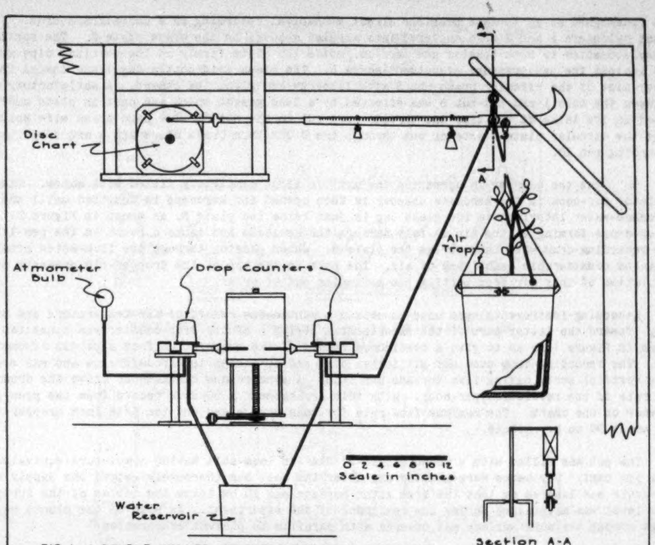
A
Disc Chart
Air Trap
Atmometer Bulb
Drop Counters
0 2 4 6 8 10 12
Scale in inches
Water Reservoir
A
Section A-A

FIG. 1—A DOUBLE-WALLED IRRIGATOR-POT WITH APPARATUS FOR RECORDING WATER-INPUT, POT-WEIGHT, AND EVAPORATION FROM AN ATMOMETER-CUP

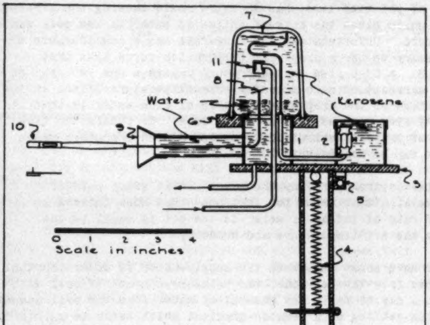
7
11
8
Water
Kerosene
6
10
9
1
2
3
5
4
0 1 2 3 4
Scale in inches

FIG. 2—SECTION-VIEW OF DROP-FORMING AND COUNTING MECHANISM

scale-beam gave a pen-deflection of 0.67 cm for a change of ten grams in weight of pot and chart-errors due to friction-effects were less than one 0.1 cm. Shifting the small weight on the scale-beam provided a convenient means for checking the deflection-sensitivity and for bringing the recording pen back onto the 9-cm range of the disc-chart. The soil-cavity of the pot was 10 inches in diameter at the top and 14 inches deep and the cut-away section in Figure 1 shows the double-walled construction. Two spouts were provided at the top of the pot for making water-connections. A glass air-trap was attached to one of these to provide visual indication that the interwall-cavity remained completely filled with water. The section-view AA shows how the supply-water connection to the other spout was made with flexible tubing on the fulcrum-axis of the scale-beam.

The flow of water to the pot was measured by a drop-counter having the same general principle of operation as that used by Ive and Richards (Rev. Sci. Instr., vol. 8, p. 86, 1937). Fig. 2 shows how the drop-counter unit was redesigned so as to make possible direct mechanical recording on a chronograph-drum. The brass cylinders 1 and 2 were soldered into annular grooves in the brass plate 3. The spring 4, being subjected to both tension and torsion, holds the plate firmly on the vertical pipe-support and against the pen-pressure adjustment-screw 5. The glass acid-bottle cap 7 was sealed in the upper side of the circular brass nut 6 with litharge-and-glycerine cement. A satisfactory closure between the tube 1 and the nut 6 was effected by a lead gasket which was cast in place and surfaced in the lathe at the time the threads were cut in the nut 6. The hard-brass wire which carries the circular plate 8 extends out through the 0.002-inch brass diaphragm 9 and supports the recording-pen 10.

To place the counter in operation the unit is first completely filled with water. The radiator air-cock in the kerosene-chamber is then opened and kerosene is admitted until the kerosene-water interface in the glass cap is just below the plate 8, as shown in Figure 2. Water-drops forming at the tip 11 fall through the kerosene and cause a notch in the pen-line on the recording-drum when they strike the plate 8. Water passing through the flow-meter often contains considerable quantities of air. The hole in the top of the dropper-tip prevents an accumulation of this air from putting the mechanism out of order.

Recording-instruments were used to obtain a continuous record of air-temperature and humidity. Toward the latter part of the experimental period a second drop-counter was connected as shown in Figure 1 so as to give a continuous record of the evaporation from a porous atmometer-cup. The recording-drum used was six inches high and 20 inches in circumference and was mounted on a vertical screw having five threads per inch. A synchronous clock-motor drove the drum at the rate of one revolution per hour. With this arrangement a 30-hour record from two pens could be made on one chart. The maximum flow-rate for this drum speed and the 5/16-inch dropper-tip was about 90 cc per minute.

The pot was filled with a known amount of Clarion loam-soil having a moisture-equivalent of 11.8 per cent. Soy beans were planted and after the soil was thoroughly wetted the supply water-reservoir was lowered so that the free water-surface was 20 cm below the bottom of the irrigator. This level was maintained during the remainder of the experiment. As soon as the plants were large enough the soil-surface was covered with paraffin to prevent evaporation.

Data and discussion--Curves showing weight of pot, rate of water-movement to the pot, rate of transpiration, air-temperature, and air-humidity are shown in Figures 3 and 4. Curve A, which shows the variation in the weight of pot with time, has an extra scale showing the average moisture-content of the soil. Curve B, which gives the rate of inflow of water to the pot, was taken directly from the drop-counter record. Unfortunately the flow-rate has a considerable effect on the size of drops so it is necessary to use a drop-size calibration-curve like that shown in the inset at the top of Figure 3. A 5°-C rise in temperature causes a one per cent decrease in drop-size (loc. cit.), but no corrections were made for this temperature-effect in the data here presented. A particular advantage of the drop-counting type of flow-meter is that it makes possible a precise determination of flow-rate as well as total flow. To obtain the flow-rate from the chronograph-record a pair of proportional dividers equipped with a special scale based on the drop-size calibration-curve may be conveniently used.

Curve C gives the rate at which water is transpired by the plant and at every point is equal to curve B minus the slope of curve A. It is seen, for instance, that when curve A is horizontal, that is, has zero-slope, the rate of inflow of water to the pot is equal to the transpiration-rate. Curves D and E give the air-temperature and humidity.

Experiments with double-walled pots have shown that when the supply-water is under constant tension and when equilibrium is approached from the wet side, the moisture-content of soil within the pot reaches a steady value within a day or two. Any removal of water from the soil causes an increase in the capillary tension, thus setting up a tension-gradient which tends to maintain constant moisture-content in the irrigator-pot. (The term capillary tension is used to refer to the negative pressure in the water in unsaturated soil, atmospheric pressure being taken as the zero-reference.) Up until May 15 curve A shows that averaged over a day's time the irrigator was able to keep up with the plant-transpiration losses, the inflow of water to the soil during the night being sufficient to compensate for the decrease in moisture-content which occurred during the hours of high transpiration-rate. On May 16 and 17, however, the daytime water-loss was considerably greater than the night-time gain. The temperature- and humidity-records show these to be hot dry days. After this time the irrigator slowly lost control of the moisture. Even during cool and comparatively humid days no substantial progress was made toward attaining former moisture-levels. The general form of the pot-weight line is closely correlated with the temperature- and humidity-curves.

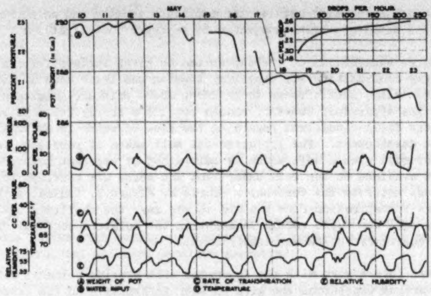

FIG. 3—CURVES SHOWING THE RELATION OF POT-WEIGHT, WATER-INPUT AND TRANSPIRATION TO AIR-TEMPERATURE AND HUMIDITY

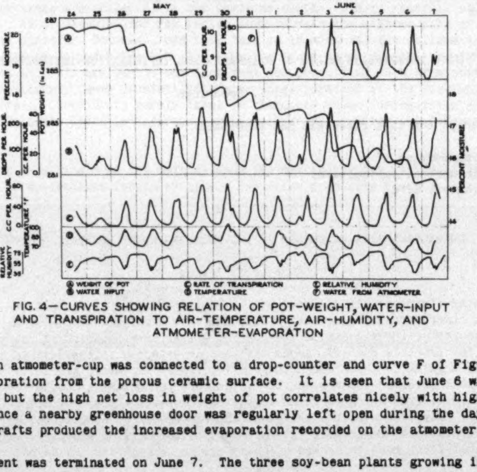

FIG. 4—CURVES SHOWING RELATION OF POT-WEIGHT, WATER-INPUT AND TRANSPIRATION TO AIR-TEMPERATURE, AIR-HUMIDITY, AND ATMOMETER-EVAPORATION

On June 1 an atmometer-cup was connected to a drop-counter and curve F of Figure 4 shows the rate of evaporation from the porous ceramic surface. It is seen that June 6 was not particularly dry or hot but the high net loss in weight of pot correlates nicely with high atmometer-evaporation. Since a nearby greenhouse door was regularly left open during the day, it is possible that air-drafts produced the increased evaporation recorded on the atmometer.

The experiment was terminated on June 7. The three soy-bean plants growing in the pot were in a healthy vigorous condition and were 32 inches tall. The roots were well nodulated and evenly distributed throughout the pot. There was some concentration of roots at the bottom of the pot and around the side, but not sufficient to prevent excellent contact between the soil and the porous water supplying surface of the irrigator.

The following moisture-samples were taken immediately after the soil was removed from the pot:

Top outside	0 to 1-cm layer	18.10 per cent
Top outside	2 to 3-cm layer	14.57 per cent
Center	10 cm from top	13.46 per cent
Middle of pot		12.86 per cent
Bottom	0 to 1-cm layer	15.67 per cent
Bottom	2 to 3-cm layer	13.84 per cent

Tensiometer-cups installed at the middle and outside edge were connected to a duplex recording vacuum gage to give a record of tension-gradients within the pot but an unexpectedly large temperature-effect in the relation between the capillary tension and moisture-content of soil raised some questions which are being subjected to separate investigation.

Before a detailed explanation of the curves can be given further information is needed regarding the capillary conductivity and capillary tension and their mode of variation with respect to moisture-content. Also, little seems to be known about moisture-gradients which are set up by growing roots. The apparatus, however, should provide a fairly reliable indication of what may be expected under field-conditions regarding the flow of water in an unsaturated soil as related to plant-root development. The irrigator-pot wall makes it possible, in effect, to surround a test-mass of soil with a soil which is maintained at constant moisture-content. The root-development is confined to the soil under test and means are provided for measuring the capillary transfer of water to the test-soil. Curve A, Figure 3, indicates that from May 10 to 15, when the average transpiration-rate was 210 cc per day, the capillary inflow of moisture to the root-containing soil was rapid enough to maintain the moisture-content. Later, with higher transpiration, the capillary inflow was insufficient.

It is hoped that future work with the apparatus will provide reliable data on auto-irrigator performance under various conditions and give further information on the extent of water-flow in unsaturated soil during root-growth.

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SOME INTERRELATIONSHIP OF RAINFALL- AND INFILTRATION-INTENSITIES

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The manuscript for this paper was not submitted.

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CHARACTERISTICS OF FLOODS IN THE SOUTHERN ROCKY MOUNTAIN REGION

Royce J. Tipton

The following discussion is directed at the characteristics of flood-flows in the State of Colorado, which comprises the major part of the Southern Rocky Mountain Region. The discussion embodies the results of investigations made by the writer over a period of years for the purpose of determining the probable size of floods that can be expected in the various drainage-basins of the region as a guide to the proper design of spillways and other hydraulic structures. The studies, as in most studies with respect to floods, are inconclusive and indicate the lack of sufficient basic data from which to reach logical conclusions concerning flood-flow magnitudes and frequencies. They indicate also the fact that regardless of conclusions which might be reached from the available basic data, with respect to the maximum floods to be expected in a given basin, flood-flows much in excess of those assumed maxima are apt to occur.

The types of floods, with their causes, that can be expected in this region first will be discussed, then the method used to arrive at the probable size of floods to be expected in the various drainage-basins of the region will be described.

In general, three distinct types of floods occur in the Rocky Mountain Region of Colorado, the difference in type being due largely to the difference in the effect the topography of the various parts of the region has upon moisture-laden air coming into the region.

These three types of floods, as defined by the writer, are: First, floods or high water resulting from the melting of snow, increased at times by rains; second, floods resulting from rainfall of several days' duration; and third, the cloudburst type of flood resulting from rainfall of short duration and high intensity.

The accompanying map, Figure 1, is a relief map of the State of Colorado on which has been indicated those areas where each type of flood is most prevalent. It may be noted that the western half of the State of Colorado consists of mountainous area, while the eastern half consists of plains area with a fairly distinct break between the two areas. During the winter the major storms come from the west and southwest, as a result of which large snowfall occurs in the high mountain area along the Continental Divide and in the San Juan Mountains in the southwestern part of the State. The major storms during the summer period come from southeast and east, resulting from the movement of air in a clockwise direction around high centers, which at times originate in the Alberta area and progress southeastward across the United States through the Lake Region and the central and southeastern states. These storms at times cause the Type-II and Type-III floods as will be explained later.

It will be noted from the map that there are four areas extending north and south through the center of the State (North Park, South Park, Headwaters of the Arkansas River, and San Luis Valley) which have been excluded from the flood-region. These areas are sheltered by mountains which largely surround them, as a result of which they receive less precipitation in both winter and summer than the adjacent areas which are not so sheltered. While precipitation of high intensity occurs at times in the high mountainous portions of some of the four excluded areas, yet those occurrences are infrequent and very local in character.

The Type-I flood is prevalent in the Colorado, White, and Yampa river basins on the Western Slope. Flood-flows occurring in these basins, except in small local areas, are not influenced to any great extent by summer precipitation. The size of the flood depends largely upon the amount of snowfall during the preceding winter. Due to the high mountains which surround the region, low-pressure areas are deflected to the north or south. Summer rainfall of high intensity is unusual. As an example, for the period 1892 to date the highest rate of precipitation experienced at Grand Junction, Colorado, was 0.58 inch in 15 minutes, the maximum rate during this storm for a 5-minute period being 0.3 inch. On the other hand, due to the high mountains bounding the area on the east and due to the fact that the prevailing path of winter storms is from the west and southwest, heavy snowfall occurs on those portions of the high-altitude area that are not sheltered. Cloudbursts purely local in character occur infrequently along the lower tributaries of the Colorado River in Colorado, principally between Rifle and DeBeque, and in the Grand Mesa Area.

The flood-peaks resulting from the melting snow are not sharp, the period of high water being sustained over an appreciable length of time. The water gradually rises in the main streams

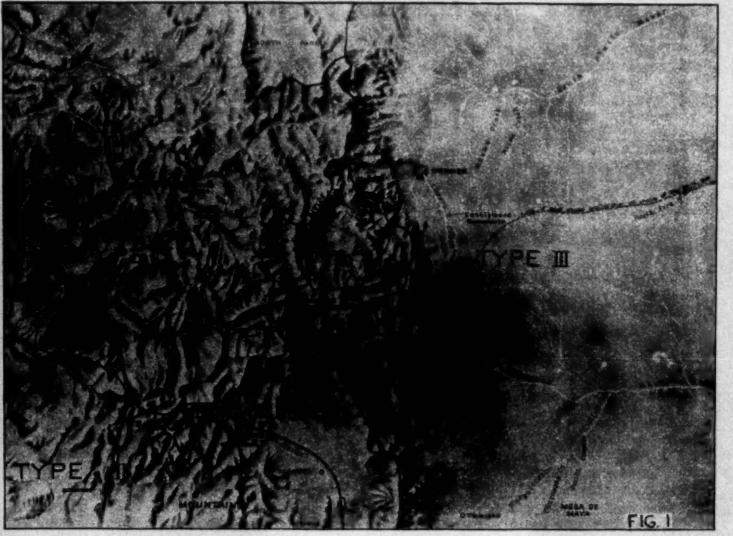

FIG. 1

over a period of time as the flood-water from the tributaries reaches the stream. The outstanding flood-flow of this type known to white man occurred in the Colorado River Basin in 1884 when a peak of 125,000 cubic feet per second was reached at Fruita near the Colorado State line and a peak of from 200,000 to 300,000 cubic feet per second was reached in the vicinity of Boulder Canyon. The snowfall during the winter of 1883-84 was the maximum of historical record.

Figure 2 shows hydrographs of typical flood-flows of the three types. The Type-I flood-flow is illustrated by the hydrograph showing the high water at Glenwood Springs, Colorado, during May 22 to June 7, 1928. The flow of the stream increased gradually at a very uniform rate for a period of nine days when the peak was reached. The flow then receded at a constant rate until a fairly uniform low-stage flow was reached about six days after the occurrence of the peak. The absolute peak was sustained for practically a full day, and was about 2.6 times the low-water flow at the time the rise commenced.

The United States Bureau of Reclamation, in cooperation with other agencies, has initiated a comprehensive system of snow-surveys in the Colorado River Basin above Boulder Canyon Reservoir. It is believed it will be possible, after a few years of records, to develop empirically the relationship between the snowfall and the next season's runoff which will permit each year of a fairly accurate estimate of the size of peak-flow which can be expected from the main stream and each of its principal tributaries.

Type-II flood-flows are prevalent in the streams rising in the San Juan Mountains in the southwestern part of Colorado, including the San Juan River and its tributaries, the Upper Rio Grande, Dolores, and Uncompagre rivers, and the Lake Fork of the Gunnison River. Snowfall has little or no effect on these floods. Flood-flows of this type are infrequent and are caused by precipitation during the summer extending over a period of days, usually culminating in a storm of fairly high intensity. The moisture-laden air causing the storm usually comes from the Gulf Region during a major movement of air in a clockwise direction around a high center located

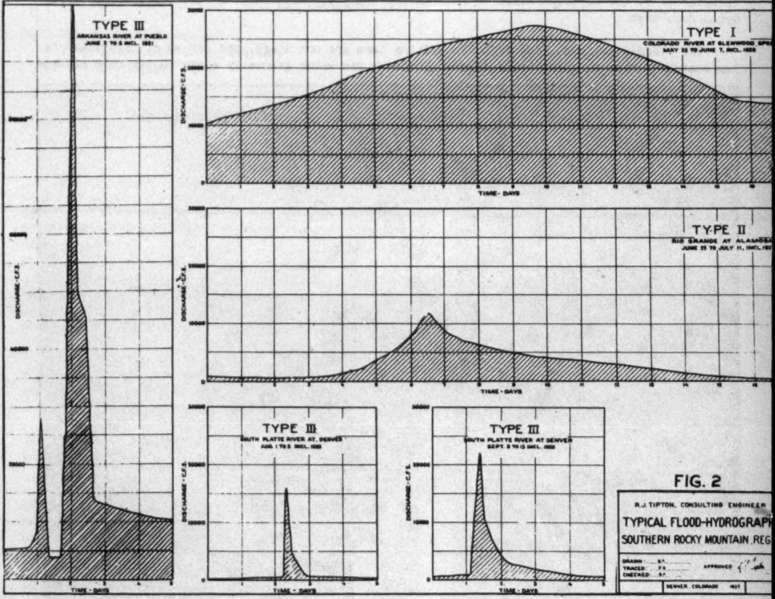

FIG. 2

R.J. TIPTON, CONSULTING ENGINEER

TYPICAL FLOOD-HYDROGRAP

SOUTHERN ROCKY MOUNTAIN REG

above the central or southeastern states. This air upon reaching the large mass of the San Juan Mountains is deflected upward, which causes condensation of moisture and precipitation. The storms usually center along the south side of the crest of the San Juan Mountains in the San Juan River Basin, and extend eastward over the Divide into the Rio Grande Basin and northwestward into the Uncompagre and Dolores river basins. The San Juan Mountains shelter the basins to the north, preventing the occurrence of intensive precipitation in those basins.

The peak of the Type-II floods are rather sharp, the flow building up rapidly and receding rapidly. A characteristic hydrograph of this type of flood, representing the flow of the Rio Grande at Alamosa for June 25 to July 11, 1927, inclusive, is shown on Figure 2. It may be noted that the flow of the stream rose over a period of about three days at an increasingly rapid rate, culminating in a peak-flow which was about 12 times the low flow at the beginning of the rise. The flow then receded over a period of several days at a progressively decreasing rate, the flow having dropped to one-half the peak-flow in a period of a day and a half. The peak-flow was about 1.2 times the mean daily flow of the day on which the peak occurred.

The outstanding Type-II floods of record occurred during the fore part of September, 1909, the fore part of October, 1911, the fore part of June, 1921, and the latter part of June and fore part of July, 1927. All of the streams heading in the San Juan Mountains were in a flood during those periods.

During the flood of 1911, rainfall occurred over the San Juan Mountains area on each of the days between September 26 and October 6, inclusive, except on October 3. The maximum reported rainfall for the period was at Gladstone in an amount of 12.12 inches. The highest intensity for a 24-hour period elapsing between readings of the rain-gage at this cooperative station was 8.05 inches on October 5. The flood-flows in some of the streams heading in the San Juan Mountains, resulting from the storm, were the highest flows historically known up to that date. Considerable damage resulted from the floods. The estimated maximum discharge of the Animas River at Aztec, New Mexico, was 30,000 cubic feet per second and of the San Juan River, near the Colorado-New Mexico State line, 40,000 cubic feet per second. The peak-flow of the San Juan at Ship Rock, New Mexico, was estimated at 150,000 cubic feet per second. At Del Norte, Colorado, the peak-flow of the Rio Grande was estimated at 12,000 cubic feet per second.

During the occurrence in 1921 rain occurred in general throughout the San Juan Mountain area for the 6-day period from June 3 to 9 with no precipitation on June 8. The highest precipitation for the period occurred on June 4 at Trout Lake amounting to 2.36 inches with a maximum intensity for a 24-hour period of 0.85 inch on June 4, followed by 0.61 inch on June 5, and 0.65 inch on June 7. The maximum 24-hour intensity occurred at Tacoma amounting to 1.43 inches on June 4.

During the storm of 1927 precipitation occurred in general throughout the area from June 26 to 29, inclusive, with the maximum intensity on June 28. Maximum recorded precipitation for the period was 5.94 inches at Palisade Lake with the maximum for a 24-hour period at that station of 2.50 inches on June 28. The maximum recorded 24-hour intensity was at Durango amounting to 2.68 inches on June 28.

It must be understood that the 24-hour intensities given above represent the amount of precipitation during the 24-hour period elapsing between the reading of the rain-gages at the cooperative stations and do not represent the true intensity for any 24-hour period.

The third, and most interesting type of flood, the cloudburst type, occurs in eastern Colorado mainly at the point where the Front Range and the plains area join, as shown on Figure 1. These floods in general are caused by moisture-laden air from the plains area, being deflected upward by the foothills along the Front Range, or other areas having a higher elevation than the surrounding region, thereby causing a sudden cooling of the air and rapid condensation of the moisture which results in precipitation of high intensity.

Cloudbursts occur suddenly without warning and are most prevalent in streams that are usually dry. Due to the aridity of the area subject to cloudbursts, vegetation-cover usually is negligible and in portions of the area the soil-cover is light. Consequently, the runoff resulting from the torrential precipitation is usually large and rapid. Dry streams in this area within a few minutes can become raging torrents.

The peaks of cloudburst flows are exceptionally sharp. The total volume of water in such a flow is small compared with the peak. Hydrographs of three floods of the cloudburst type are shown on Figure 2. One hydrograph shows the flow of the Arkansas River at Pueblo, Colorado, during the flood of June, 1921. A small peak occurred on the morning of June 3. The flow then receded to less than 5000 cubic feet per second and remained at that stage until about 6 p.m. on June 3. The flow then increased rapidly at a fairly uniform rate until an estimated momentary peak-flow of 100,000 cubic feet per second was reached. Within 17 hours after the peak the flow had receded to 10,000 cubic feet per second. The average flow during the 25-1/2 hours when the flood was passing was about 45,000 cubic feet per second, the peak being 2.22 times greater.

On Figure 2 is shown also the hydrograph of the flood-flow which resulted in the South Platte River at Denver from the breaking of Castlewood Dam on Cherry Creek, about 40 miles southeast of Denver, on August 3, 1933. The breaking of the Dam was due to its being overtopped by a flood-flow caused by a cloudburst above the Dam. The flow of the South Platte at Denver on the morning of August 3 increased in a few minutes from about 500 cubic feet per second to a momentary peak of 16,000 cubic feet per second. After the peak was reached the flow receded rapidly, reaching a low-water stage of about 650 cubic feet per second at the end of the day. The peak was 32 times the low-water flow at the beginning of the flood and about seven times the mean flow during the day on which the peak occurred.

The third hydrograph of the Type-III flood on Figure 2 represents the flood-flow in the South Platte River at Denver caused by cloudbursts near Denver on September 9 and 10, 1933. Twenty-two thousand cubic feet per second, the highest recorded peak in the South Platte River at Denver, resulted from this storm. The flow of the River increased in less than six hours from about 600 to 22,000 cubic feet per second and then decreased rapidly to a flow of about 3000 cubic feet per second about 13 hours after the peak. The peak-flow was about 37 times the low-water flow immediately preceding the peak and about 2.4 times the mean daily flow for the day on which the peak occurred.

The similarity between the hydrographs resulting from cloudburst flows unrestrained and the hydrograph of the flood-flow resulting from the breaking of Castlewood Dam may be noted.

Cloudbursts in Colorado occur most frequently in the Purgatoire River Basin, a tributary of the Arkansas River. The next basin in order of frequency of occurrence of cloudbursts is the Fountain River Basin and the third is the area around Denver, including Cherry, Plum, Deer, and Turkey creeks and the canyon section of Clear Creek, all short tributaries of the South Platte rising in the foothill region of the Front Range.

The Purgatoire River, for a distance of about 75 miles above its mouth, flows in a deep circuitous canyon. The major tributaries of the River throughout this section flow also in deep canyons, the most notable of which are Smith and Chaquaqua canyons. These canyons head near the Colorado-New Mexico State line at the foot of Mesa de Maya, a massive basaltic outcrop. On the west side of the Purgatoire Canyon another mesa rises with rather precipitous slopes on the east side, which mesa forms the divide between the Purgatoire and the Timpas river basins.

The Purgatoire River Canyon, together with the canyons of its tributaries, are virtual chimneys which induce upward drafts of air. At times large volumes of moisture-laden air are drawn up the canyons from the plains regions to the north and northeast. This air is deflected upward by the numerous promontories in the canyons, and infrequently by the Mesa de Maya, all of which causes intensive precipitation and resulting flood-flows.

Due to the lack of development in the Purgatoire River Basin very little damage results from these flood-flows although at times some damage is caused in the main Arkansas River Basin below the mouth of the Purgatoire. The outstanding flood-flow from the standpoint of damage in the Purgatoire River Basin occurred in October, 1904. Forty-five thousand cubic feet per second passed through Trinidad, Colorado, and about 70,000 cubic feet per second passed Lamar, most of which came from the Purgatoire.

The Fountain River flows southward parallel to and immediately at the foot of the Front Range, joining the Arkansas River at Pueblo. Its principal tributary, Monument Creek, rises in the Black Forest at the crest of the divide between the Arkansas and South Platte river basins east of Palmer Lake. This divide reaches an elevation of some 8000 feet. The higher elevation of the headwaters of Monument Creek, and the Front Range on the west of Fountain River, are topographic features which make for the frequent cloudburst occurrences in the Fountain River Basin.

Considerable damage has resulted to Colorado Springs at various times from cloudburst flows in the Fountain River. The most notable of such occurrences was on May 30-31, 1935, when a peak-flow of some 50,000 cubic feet per second occurred at Colorado Springs.

As may be noted by the map, the short tributaries of the South Platte River rising to the south, southwest, and west of Denver lie in the areas which are conducive to the formation of storms which result in cloudburst flood-flows. Those flows which have caused the most damage have occurred in the Cherry Creek Basin, which heads at the Arkansas-South Platte Divide opposite the headwaters of Monument Creek.

The outstanding floods of cloudburst nature which have occurred in Colorado within the memory of the white man were the so-called Pueblo Flood of June 5, 1921, and the floods which occurred in the Republican and South Platte river basins on May 30-31, 1935. The Pueblo Flood had a peak of over 100,000 cubic feet per second at Pueblo and approximately 200,000 cubic feet per second at Lamar. It is believed that the storm which caused this flood-flow was due to the major topographic feature which exists in the Arkansas River Basin in the vicinity of Pueblo. Extending from Pueblo to Canyon City the topography forms a major funnel with the small end near Canyon City. The north side of the funnel is formed by the acute bend in the Front Range a short distance north of Pueblo. The south side of the funnel is formed by the Wet Mountains which extend southeast from Canyon City toward Trinidad. The draft-inducing properties of this major funnel were sufficient during the storm, which caused the Pueblo Flood, to pull into the area immediately above Pueblo large quantities of moisture-laden air along the Front Range from the north, from the plains area to the east, and along the Wet Mountains from the southeast. This caused a high concentration of moisture-laden air in two small areas above Pueblo which resulted in very intensive precipitation. The areas of intense precipitation are shown on Figure 1. Unofficial records indicate a total precipitation during the afternoon and night of June 3 over a part of one of the areas of 14 inches.

The storm of May 30-31, 1935, was caused by warm moisture-laden air from the Gulf Region striking a massive cold front, some 50 to 75 miles east of the Front Range. This cold front had the same effect as the Front Range causing sudden condensation of moisture and intensive precipitation. The flood-flows resulting from this storm were the largest of record in the various

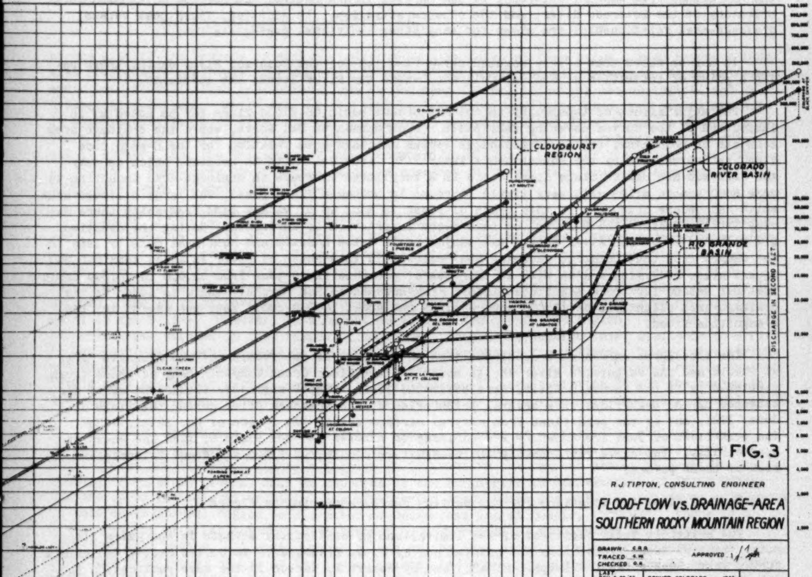

FIG. 3

R J. TIPTON, CONSULTING ENGINEER

FLOOD-FLOW vs. DRAINAGE-AREA
SOUTHERN ROCKY MOUNTAIN REGION

basins over which the major portion of the storm occurred. The line of most intense precipitation during the storm is shown on Figure 1. Several unofficial records indicate total precipitation of about 15 inches during the storm at several points along the line.

Due to the lack of basic data with respect to rainfall-intensities over the Southern Rocky Mountain Region it is impossible to determine probable maximum flood-flows by the rational method. It is also impossible to apply the unit-hydrograph method. When it became necessary to devise some means for determining probable flood-peaks on account of the importance of hydraulic structures being investigated, designed, and constructed in the Region, a method was devised which utilized all basic data available so far as actual recorded flood-flows were concerned. The method was somewhat different than any method heretofore used. Figure 3 is a diagram showing the relation between estimated peak-flows of various magnitudes and drainage-area for the various drainage-basins of Colorado as developed by the method.

Probability-curves first were prepared for all flood-flows recorded at each of the gaging-stations located on the streams investigated. These curves were not used necessarily to estimate the probable frequency of occurrence of floods of various sizes.

The curves were used mainly to put all of the data, in so far as it was possible, on a common basis. It was believed that better results would be obtained by this method than by plotting individual maximum occurrences on the graph and drawing envelope-curves around the points representing these occurrences. The so-called 10,000-, 1000-, and 100-year floods for each gaging-station in a particular drainage-basin was plotted against the drainage-area above the gaging-station on paper with a log-log scale. These various magnitudes of floods are labeled on Figure 3 as B, C, D. The B-magnitude of flood is indicated by the open circle; the C-magnitude by the open circle enclosing the closed circle; and the D-magnitude by the vertical cross. The various sets of points along a given stream were then connected by curves. Several sets of curves are shown on Figure 3, representing the Colorado River from Sulphur Springs to Boulder Canyon Dam; the Rio Grande from Wasson, Colorado, to San Marcial in New Mexico; the Roaring Fork which is a tributary of the Colorado River; and the cloudburst-region. In addition, flood-peak versus drainage-area relationships are shown for many other individual gaging-stations.

It may be noted that a very regular curve resulted for the Colorado River Basin, there being a point of inflection at Fruita, Colorado, where the River leaves the mountains.

The major effect of topography in the Rio Grande Basin on flood-flows may be noted by an inspection of the curves covering that Basin. From Wasson to Del Norte, where the drainage-area consists of mountains, the flood-discharge versus drainage-area relation for the B-magnitude flood is represented by the equation $Q = 194A^{0.670}$. From Del Norte to Lobatos, which is near the Colorado-New Mexico State line, there is a very large increase in drainage-area amounting to some 6600 square miles with very little increase in probable flood-peak. The large drainage-area which has become tributary to this reach of river is made up of valley land from which there is very little runoff. The B-curve for this reach is practically horizontal, having the equation $Q = 21{,}200A^{0.023}$. The River enters the canyon again below Lobatos and continues more or less in the canyon from that point to Buckman, New Mexico. To this reach of river is added some 240,000 square miles of drainage-area with an increase of probable flood-peak from 25,000 to 70,000 cubic feet per second for the B-magnitude flood. From Buckman to San Marcial, there is added to the drainage-area slightly over 10,000 square miles and about 10,000 cubic feet per second for the B-magnitude flood.

The cloudburst curves were developed from an analysis of the records of the Fountain River at Pueblo and the Purgatoire River at its mouth and the Clear Creek Canyon. Many of these flows, particularly of the Fountain River, were estimated flows. The B-magnitude cloudburst curve was exceeded by the peak-flows from several tributaries of the Arkansas River during the flood of June, 1921, and by the peak-flows from several streams during the floods of May 30-31, 1935. The peak-flows of 1921 are shown by x's enclosed in circles and the peaks of 1935 are shown by open circles. The curve representing the A-magnitude cloudburst flood was drawn to encompass most of those points.

Table 1 gives the equations for the various curves appearing on Figure 3.

The writer is fully cognizant of the limitations of statistical methods in analyzing flood-data. Some of these limitations are pointed out by J. J. Slade, Jr., in United States Geological Survey Water-Supply Paper 771 (pp. 421-432) and by Robert E. Horton in the same publication (pp. 433-450). In addition to the limitations pointed out by these writers, it is believed impracticable to extend the ordinary available short-time record to a 1000- or 10,000-year period as would

Table 1--Flood-flow formulae for the Southern Rocky Mountain Region (from Figure 3)

[$Q = CA^a$, where Q = peak-flow in cubic feet per second, A = drainage-area in square miles, and C = constant]

Drainage-basin or region (1)	Portion of basin (2)	Drainage-area limits (3)	Magnitude		
			B Peak-flow (4)	C Peak-flow (5)	D Peak-flow (6)
		sq. miles	cfs	cfs	cfs
Colorado River (Type I)	Yampa at Steamboat to Colorado at Glenwood Springs	520 to 4600	$60A^{0.818}$	$50A^{0.818}$	$57A^{0.770}$
	Glenwood Springs to Fruita	4600 to 17000	$83A^{0.780}$	$86A^{0.753}$	$37A^{0.822}$
	Fruita to Black Canyon	17000 to 165000	$1080A^{0.515}$	$1080A^{0.495}$	$1670A^{0.430}$
Rio Grande (Type II)	Wasson to Del Norte	700 to 1400	$194A^{0.670}$	$612A^{0.472}$	$417A^{0.485}$
	Del Norte to Lobatos	1400 to 7700	$21200A^{0.023}$	$11500A^{0.062}$	$900A^{0.060}$
	Lobatos to Embudo	7700 to 10000	$12.5A^{0.854}$	$10A^{0.854}$	$10A^{0.820}$
	Embudo to Buckman	10000 to 14000	$0.000025A^{2.28}$	$0.0014A^{1.814}$	$0.0070A^{1.61}$
	Buckman to San Marcial	14000 to 26000	$8900A^{0.216}$	$760A^{0.430}$	$1700A^{0.310}$
Cloudburst Region (Type III)	....	10 to 4000[a]	$1450A^{0.555}$	$870A^{0.571}$	$470A^{0.580}$

[a] For A-magnitude $Q = 4400A^{0.555}$ cfs.

be the case if the results of probability-studies were taken at face value. Even though a long-time record were available, the analysis of such a record by probability-method, it is believed, would lead to fallacious conclusions, due to the many factors affecting meteorological and hydrological phenomena. While many of the factors, no doubt, are fortuitous, yet others are not. It appears that years of high rainfall and years of excessive flood-flows occur in groups as do years of drouth. While there is no indication from available data that definite cycles occur, yet it appears that the frequency of occurrence of flood-flows, years of high runoff, or years of drouth if considered on an annual basis is somewhat different than would be expected if the occurrences were entirely fortuitous.

However, it is believed fair results were obtained by the writer's method in determining the flood-characteristics of the Colorado River and Rio Grande areas. The flood-producing characteristics of each portion of the Basin were automatically taken into consideration by the method used in analyzing the data. Whether the maximum size flood is represented by the B-magnitude curve is not known. Yet it is known flood-flows represented by that line are very infrequent, and it is believed a line representing the maximum flood-flows would be roughly parallel to the B-line. However, this cannot be said of the cloudburst region. Records of runoff for only three streams in that region of sufficient length and accuracy were available to arrive at any conclusions with respect to probable size of cloudburst flood-flows. These three streams are somewhat widely separated. The curves, therefore, derived for the cloudburst region are very preliminary and do not reflect necessarily the individual characteristics of all the basins in the cloudburst region. The cloudburst curves are used by the writer only as a very general guide.

The above discussion is illustrative of typical efforts of a practicing engineer over a period of years to devise a tool, from insufficient basic data, for solving specific problems. There are no precipitation-stations located in Colorado in the regions where the greatest intensity of rainfall occurs, such as the area of the Purgatoire in the vicinity of Smith Canyon and the upper Fountain River Basin. As a matter of fact, there are only two recording rain-gages in this whole general region, one located at Denver and one at Pueblo, Colorado. There is a great need for detailed research with respect to occurrences of cloudbursts in the Southern Rocky Mountain Region. It would appear to the writer that after a period of research with recording rain-gages located at the proper points, and companion gaging-stations on the streams which are subject to frequent cloudburst-floods, coupled with air-mass analyses, a technique of forecasting could be developed whereby occurrences of cloudbursts could be predicted with possibly some estimate of probable volume.

It is sincerely hoped that various governmental agencies, such as the Weather Bureau, the Geological Survey, and the Soil Conservation Service, will initiate a continuing study in this region of cloudburst flows in an effort to work out something much more definite than the writer has been able to do with the data available Attention is called to the report of the National Resources Committee on Deficiencies in Basic Hydrologic Data which points out the economic importance of collecting more of such data.

1231 First National Bank Building,
Denver, Colorado

JOINT MEETING WITH THE SOCIETY OF AMERICAN FORESTERS

The Section of Hydrology held a joint meeting with the Society of American Foresters at Denver, Colorado, June 22, 1937. Nine papers were presented. Eight of these will be published in full in the November 1937 number of the Journal of Forestry, as follows:

The economic and social value of watershed management. Charles A. Lory, Colorado State College of Agriculture and Mechanic Arts, Fort Collins, Colorado.

Natural vegetation as a factor in the losses and yields of water. Joseph Kittredge, Jr., University of California, Berkeley, California.

Laboratory measurement of evapo-transpiration losses. Ralph L. Parshall, Colorado Agricultural Experiment Station, Fort Collins, Colorado.

A new epicycle of erosion. Reed W. Bailey, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Land-use patterns needed in watershed management to control erosion and stabilize streamflow. W. C. Lowdermilk, Soil Conservation Service, U. S. Department of Agriculture, Washington, D. C.

Precipitation and runoff in relation to altitude in the Rocky Mountain Region. F. C. Hart, U. S. Bureau of Reclamation, Denver, Colorado.

Stabilizing stream-flow as viewed by a forester. C. L. Forsling, U. S. Forest Service, Washington, D. C.

Hydrologic aspects of stream-flow stabilization. Robert E. Horton, Voorheesville, New York.

The ninth paper, "Tree-rings versus runoff in the South Platte River Basin," was presented by H. L. Potts of the Denver Water Board, Denver, Colorado. This paper will not be published at present since the author has not yet completed his investigation.

NATIONAL RESEARCH COUNCIL

TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION

SECTION OF HYDROLOGY

REGIONAL MEETING

JUNE 25 AND 26, 1937

DENVER, COLORADO

REPORTS AND PAPERS

SOUTH CONTINENTAL DIVIDE SNOW-SURVEY CONFERENCE

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
JULY, 1937

AMERICAN GEOPHYSICAL UNION

Regional Meeting

SOUTH CONTINENTAL DIVIDE SNOW-SURVEY CONFERENCE

JOINT REGIONAL MEETING WITH

SECTION OF HYDROLOGY

Denver, Colorado
June 25 and 26, 1937

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THE PRESENT STATUS OF SNOW-SURVEYING AND IRRIGATION WATER-SUPPLY FORECASTING IN THE WEST

James C. Marr

"Picture": Years ago the foundation of a structure was solidly built, starting from a firm base and thence laid flawlessly to the level where the superstructure could be started. The skeleton of the edifice to be has since sprung into view. It consists of a great framework of innumerable members dovetailed and secured one to the other through eleven stories and finally topped off by a roof-structure designed to hold the assemblage together and to protect it. The base for this building is the need throughout the West to know what the water-potentialities of the mountain snow-cover are. The foundation is the weight-method of determining the density of snow and the "course-method" of snow-surveying for forecasting stream-flow and soil-moisture conditions. The eleven stories are conceived to be the eleven western states where this work is in progress; the braces and supports in each the numerous organizations and individuals who cooperate in the endeavor. The roof-structure is the Federal coordinating agency, the Bureau of Agricultural Engineering, United States Department of Agriculture. The structure is dedicated to "Irrigation water-supply forecasting," but in reality it is predestined to accommodate the many and variable needs for predicting the effects of accumulated snowfall. The newer and less well-tested parts of this work--the superstructure of cooperative effort and provisions for rendering service--should, perhaps, be sounded and checked over to ascertain if they are sufficiently strong and ample enough to meet requirements.

Cooperation--At first glance and especially as viewed with limited horizon it might appear unsafe and a shirking of responsibility to trust so difficult and all-important a task as the snow-surveying to hundreds of cooperators, but such has not been the experience.

This job is often so difficult that the mere payment of good wages for the service is no assurance that it will be honestly performed. To be successfully carried out it must usually mean something more than temporary employment. There is one case on record of two men who could not find enough moral persuasion in their pay ($7.50 per man-day) to see them through with the difficult trip they were instructed to make. They turned in some snow-measurements all right but, as revealed by resurvey, they stopped short of the place where they were supposed to make them. Indeed, a great many of these survey-trips require the presence of one, mightily inspired and physically capable, who will reach the snow-course at any cost in expended energy and hardship and who may be counted upon to return with the correct information. Strong young men who have some responsibility in correctly interpreting the snow-measurements and whose stake in the activity is their year-round employment and interest in such work are best suited to lead snow-survey parties. No one organization which operates in the West is equipped with a sufficient and qualified personnel who are properly located in all instances to step in and take charge of this operation. Provision might be made whereby Bureau of Agricultural Engineering could expand its present permanent force of engineers to meet these requirements but no one, it is thought, after considering the cost would harbor that idea. Figure that cost. There are upwards of 700 snow-courses. Men of at least $2000 to $3000 caliber would be required as chiefs of parties. Within a few years those originally employed for the purpose would become physically unfit for the task and would have to be duplicated by younger men. Happily, in practically all cases, there exists local responsibility for keeping in touch with the snow-situation which, if properly nurtured, may be depended upon for the detailed supervision of snow-surveys. Such has had to be the general plan of organizing the snow-survey work. Obviously, the stability of our whole structure depends upon the care with which each member of this assembly of cooperators has been selected and how secure are the relations which hold it together.

In making a selection of cooperators care has been exercised: To enlist the greatest degree of responsibility attainable; to avoid overloading any one cooperator with work and expense beyong that which may be readily taken care of; and to make the task as simple and as free of burdensome details as may be.

To illustrate: The resulting arrangements for snow-surveys on Boise River Watershed in southwestern Idaho are based upon these considerations and the outlook there is for uninterrupted, accurate records, even though some of the surveys require difficult and dangerous trips in winter. There are seven snow-courses in this area and seven active cooperators. The Bureau of Agricultural Engineering functions here as elsewhere. It supplies the equipment for measuring the snow; establishes the snow-courses; makes and keeps intact all of the arrangements for snow-surveys; assembles, interprets, and makes available the snow-cover information; and shares--less than is desirable, but as much as possible--in the expense of the surveys. Four shelter-cabins for the survey-parties were required. These have been provided and are kept stocked with food, fuel, and bedding jointly by the irrigation-interests of Boise Valley, the United States Forest Service, the United States Biological Survey, and the United States Bureau of Agricultural Engineering. Four of the seven snow-courses are regularly surveyed by the Boise Irrigation Project management assisted in part by other farmer organizations of Boise Valley and by local representatives of the United States Biological Survey and the Intermountain Forest and Range Experiment Station, all of which have need for the snow-data. The Superintendent of the Boise Project, William E. Tuller, and/or his chief hydrographer, L. P. Jensen, head the parties. The Government men who usually accompany them have equal standing and responsibility in their organizations. It would be impossible to get together a more responsible and competent snow-survey party than is had. To make the round trips to these courses requires approximately 150 miles travel through mountainous country on skis. A fifth course is handled by permanent employees of professional standing of the Intermountain Forest and Range Experiment Station who are stationed, during the winter, in the vicinity of the course. The remaining two snow-courses are surveyed by resident observers, one of whom is paid for the service by the United States Bureau of Agricultural Engineering and the other by the Boise River Board of Control through William E. Welsh, Watermaster for Boise River. These two paid observers are resort-caretakers who alternately work for Salmon National Forest during the summer as construction foremen and take care of "Dude" ranches located near the snow-courses during the winter. Their dependability has thus been proven. The further arrangement is that the supervisor of Salmon National Forest acts as the responsible local cooperator. In each one of these cases the cooperator has need for the snow-information procured by or through him. Furthermore, all such information pertaining to the watershed is of value to each of the seven or more cooperators--so, these arrangements make for responsibility as among the several participants which adds to the assurance that each will do his part. Thus, we might test our present set-up for the many secondary drainage-basins. Undoubtedly, weaknesses can be found in some of them which will have to be strengthened, but experience and circumstances warrant that we seek this cooperative material for the mending jobs as well.

The quality and quantity of voluntary support had from our cooperators bespeaks louder than words of the importance of this activity to them and of the responsibility that may be entrusted to them. Counted in value of all services, supplies, and facilities which they furnished for the purpose during 1937, their contributions this year have amounted to more than $200,000. The mass of excellent records supplied by them gives final proof that they may be counted upon to render this invaluable service if they are properly treated. Would that we might have a precise statement from each setting forth the reasons for their interest. Lacking these, impressions gained through personal contact with quite a number of these agencies may serve to show, at least in part, the character of strength in this cooperation. The most important of them are thus catalogued as follows.

Perhaps the greatest amount of enthusiasm is had for snow-surveying and water-supply forecasting throughout the West by the irrigated-farm population. The reason for their interest is obvious. The nearer they know how much water is going to be available for their crops the more profitable will be their operations. Timely warning of impending drought very often means to them a fiarly successful year when otherwise the reward for their labors would be failure. If well organized and managed and not too far from the source of their water-supply these, as exemplified by the Boise Irrigation Project management, are among the most dependable cooperators.

To the same end, but for a different reason State engineers, or those charged with administration of the waters of a State, each aid the program to the fullest extent allowed by authority granted them. In quite a few cases State legislatures have provided substantial appropriations for the purpose. Such officials are sympathetic to the activity, of course, because of the information it yields. R. W. Faris, State Commissioner of Reclamation of Idaho, expresses this viewpoint as follows in his Ninth Biennial Department Report:

> "The ever-increasing use and demand for water for irrigation, mining, power, and other beneficial purposes, and the constant and persistent decrease in the water-supply make it imperative that some means be devised whereby the water-supply likely to be available for any year may be predicted in advance with a reasonable degree of certainty to the end that the water-users may plan their operations to conform to the water-supply. Most of the water to sustain the streams and other sources of water-supply comes from the melting of snow in the high mountains. . . . .
>
> "In 1935, Congress passed a bill appropriating $15,000 for the year 1935 and a like amount for 1936 to cover the expense of systematic and coordinated snow-surveys in Idaho and adjacent states, and named the Bureau of Agricultrual Engineering, United States Department of Agriculture, as the agency through which such investigations should be carried on. . . . .
>
> "This Department has lent its moral support and cooperated with the Department of Agriculture in its work in connection with its water-supply investigations as far as possible, but has not been able to contribute any of the most essential requirement, that is, money. It is suggested and recommended that after conference with the committees on appropriations of the coming

sessions of the Legislature, representatives of the United States Bureau of Agriculture and this Department, that a substantial appropriation be made available to the Department of Agriculture to assist and further the work already under way."

Because of this favorable attitude of their supervising officers, the State engineers and, owing to a direct responsibility for handling water, stream-watermasters are also leading advocates for snow-surveys. If they are old at their jobs and are adequately financed, they make excellent and willing cooperators.

Since the United States Bureau of Reclamation is either directly or indirectly responsible for the success of many of our large irrigation-projects it is and for a long time has been actively engaged in snow-surveying and water-supply forecasting in the watersheds where their projects are located. With the initiation of this work on a large scale by the Bureau of Agricultrual Engineering two years ago the Bureau of Reclamation entered whole-heartedly into the program upon a cooperative basis and may be said to have adopted the procedure as one of its regular seasonal operations. In these cases the local supervisor of snow-surveys is an engineer of high standing with maximum amount of responsibility for results.

The same things may be said about the Indian Service though the scope of its activities in this respect is less. As with the Bureau of Reclamation, it participates in the snow-survey work only in localities where it is responsible for irrigation-projects--in this case, Indian irrigation projects, which are not so numerous.

The United States Forest Service, like the remaining cooperators, is interested in snow-surveys for wholly different reasons. Aside from a disposition to render all-possible aid to so worthy a Government activity, which we believe to be general with all cooperators, this Service looks to snow-surveying as a means for predicting fire-hazard and grazing conditions on national forests so that it may be better prepared to combat the former and properly administer the latter. The following Associated Press dispatch of June 1, 1937, is illuminating in this respect: "Drouth 'doubles' flame-hazards in National forests--Drouth has 'doubled' the danger of disastrous fires in 24,000,000 acres of National forests in far western states, the Forest Service said." The attitude which this fellow Government organization has assumed towards snow-surveys and the cooperation for which it calls is expressed as follows by Major Evan W. Kelley, Regional Forester, Region 1, in a circular letter to supervisors:

"Some time within the next month or so, Mr. J. C. Marr of the Bureau of Agricultural Engineering, will visit your Forest to outline to you the snow-gaging work of that Bureau and to learn from you the extent to which you can cooperate in increasing the gaging-stations in the high country of the Columbia River Watershed. In northern Idaho, western Montana, and eastern Washington, such topography is about 100 per cent within the National Forests.

". . . . If this activity is to be started and conducted on a scope merited by the high purposes to be served by it, the various agencies of the Government directly or incidentally interested must cooperate to the fullest practical extent. That we should do our best in this connection goes without saying. Apropos of this spirit, I know that you will give Mr. Marr a cordial welcome, will give him such time as may be necessary to permit him to outline his plan, and will arrange to make available to him such facilities as you can contribute.

"My thought is that in many instances district-rangers can make measurements; in other instances, a designated man of the game-survey forces; the services of the caretakers at some of our back-country headquarters may be enlisted; also those of dependable miners in the high country of the Nezperce. Other possibilities undoubtedly may occur to you. At any rate, let us do our best."

Owing to the wide area administered by our national Forest Service, the high-type men who make up that Federal organization, and the strategic location, the physical fitness and ability otherwise of these men to handle snow-survey work, the importance of this cooperation is outstanding both in quantity and quality.

The status of the National Park Service in these respects is quite similar to that of the United States Forest Service. The opportunity that it has to participate in snow-surveying is much less, of course, but it has been found equally willing and able to carry on this work. Where national parks are involved, the responsibility for snow-surveying has been placed in its hands and the resulting performance has been excellent.

Missouri River and North Pacific divisions of the Corps of Engineers, War Department, are important cooperators for the reasons that they have tremendous constructions under way at Grand Coulee and Fort Peck and are, therefore, concerned about flood-prospects on Columbia and Missouri rivers. Their interest, however, is broader and more lasting than is thus implied. Flood- and navigation-problems on all such major streams as these are the responsibility of this branch of the Government service. It is, therefore, reasonable to assume that the present support from the War Department will be continued and possibly on a broader basis if needed.

There are a few special reasons which also bring the United States Biological Survey into this picture. The Migratory Waterfowl Division operates numerous naturally inundated areas as feed-grounds and refuges for wild life. Its interest in the water-supplies for these areas is of the same order as that of the irrigation-farmer. There must be forewarning of the quantity of water that will be available for producing feed and maintaining bodies of live water. Also, the Division of Game Management is concerned with snow conditions in connection with the care and control of game-animals. Among the caretakers of the refuges and the men who roam the woods country during the winter to study, care for, and control wild life there are those who are proving to be excellent snow-observers for their own organization as well as for the whole Federal snow-survey program.

Hydroelectric companies as a group are also among the agencies which employ snow-surveying as a basis of operation. In some cases they began this work on their own initiative years ago and in others, upon being invited to do so, started it during 1936. In either case they are now highly valued cooperators in the general program. Their interest lies principally in the regulation of reservoirs for power-purposes and preparation for eventuality of drought. The activity is carried on by them with exactness.

Nearly all of the State agricultural experiment stations are numbered among cooperators which represent all of the interests within a State. Two of them are the leaders for their State in this endeavor. Their interest is general with regard to the research and promulgation angles of the work, though several participate in the operating end of the program. Large value has resulted from agreement by the Bureau of Agricultural Engineering and by these recognized advisory State agencies as to the merits and possibilities of snow-surveying.

One weakness has become apparent in most of these cooperative arrangements. There have been numerous requests for support by way of compensation for assistant surveyors, funds for constructing, equipping, and stocking shelter-cabins and for skis or snowshoes, which it has been possible to satisfy only very meagerly. This deficiency, of course, occurs in the supporting appropriations by Federal and State governments.

Provisions for rendering service--By Act of Congress the Bureau of Agricultural Engineering is charged with the responsibility of coordinating, standardizing, and extending snow-survey work in the West and with the further duty of effecting an irrigation water-supply forecast-service based thereon. This has called for a snow-survey program, which could be carried out only by enlisting the services and support of a wide diversity of interests in snow-surveying. The program which adequately serves as the basis for complete and comprehensive irrigation water-supply forecasts incidentally provides the basic data upon which numerous other predictions may be made. The cooperative structure of the snow-survey program places upon the Bureau of Agricultural Engineering the moral responsibility of designing that program to conform, as nearly as may be, with every need. That obligation, however, cannot include interpreting the data for flood-stage predictions. The essential purpose has been prescribed in the interest of avoiding duplication of effort by Government agencies. It is stipulated in an agreement of understanding between the Bureau of Agricultural Engineering and the Weather Bureau, which bears the approval of our Secretary of Agriculture. This agreement, of course, affects only the two Bureaus and does not constitute a deterrent to other cooperators. It reads in part as follows:

"The Bureau of Agricultural Engineering will cooperate with the Weather Bureau and with other Federal and State agencies in determining the depth and water-content of snow-cover on watersheds of the arid States; in making annual forecasts of the total and seasonal water-supply of streams which will be available for irrigation-purposes; in coordinating the seasonal stream-flow forecasts prepared by State agencies on inter-State streams used in irrigation; in determining the relation of mantle-cover, soil-type, and soil-moisture to irrigation-water supplies from snowfall; and in conducting research work in physical factors other than meteorological that affect seasonal irrigation water-supply forecasting. It will also make available to the Weather Bureau all snowfall-data as soon as obtained for use in the Weather Bureau's river-and-flood service, and also for prompt publication. Furthermore, the Bureau of Agricultural Engineering will not . . . . . make forecasts of flood-stages in any stream . . . . ."

Out of this Act of Congress, the departmental ruling and circumstance there have developed the following services:

There are being procured and disseminated currently by means of radio broadcast and mimeographed reports snow-survey results for more than 650 snow-surveys which cover all or portions of eleven western states. Each principal drainage-subdivision is dealt with separately in this manner. A large percentage of the surveys are made monthly from January 1 to May 1 each year, thus providing material for circularizing each month during the winter.

All results excepting those for the May 1 survey are included in the final snow-bulletin of the year by United States Weather Bureau publication, "Climatological data," and which is issued about April 15. In this case, also, the material is published separately for major drainage-areas.

These releases from time to time by the Bureau of Agricultural Engineering, including that furnished to the Weather Bureau, are accompanied by statements of the irrigation-outlook or by seasonal irrigation-water forecasts. The statements for the earlier months of the winter are necessarily mere comparisons of snow and soil-moisture conditions with those for similar dates during previous years. Though eagerly looked forward to by irrigation-interests, these are premature as forecasts and, therefore, have uncertain value. The value of the measurements in early winter should not be gaged, however, by this one use. They are quite necessary for other applications such as operation of hydroplants, preservation of wild life, practice of winter-sports, etc. The principal purpose served by issuing these earlier reports is, therefore, to place into the hands of interested cooperators the snow-measurements which will permit them to formulate conclusions for their own special purposes. Judging from requests for these data, it has appeared important that they be made as complete as possible for the whole country and that they be promptly released.

The seasonal irrigation-water forecasts accompany release of the March 1 and April 1 snow-cover data. For many of the interior, irrigated valleys forecasting to a fine degree, that is, definite figures setting forth the volume of water to be expected, is warranted by long and successful operation of the service. In these cases farmers planned and planted their crops in accordance with the forecasts not only for the present season, but for several years. Elsewhere there existed only the snow-cover measurements and the resulting runoff for the immediately preceding year to suggest what might be the meaning of this year's snow-survey data. Such was the insecure basis for much of the forecasting this year, but the information was released because it was needed and because it was very much better than fanciful guesses and uncertainties which would have dominated had it been withheld. Now that time is beginning to enscroll finis to this year's picture of snowfall to runoff we may partially judge the value of the forecasts which started to appear months ago and which culminated in final predictions on the first of March for some regions and on the first of April for others.

The story for this year is unspectacular, or so it has been written in forecasts. It has been stated and now appears certain that the West will not be visited this spring by damaging floods, nor during the coming summer by wide-spread shortage of water as a result of last winter's snow. Happily, though destructive of interest in the development of our subject, there may not be cited either great flood-damage forestalled or loss from severe drought saved. The benefits, if such there be, lie in the experience had and confidence gained with successful forecasting.

U. S. Bureau of Agricultural Engineering,
Boise, Idaho

FURTHER IMPROVEMENT OF SNOW-SURVEY APPARATUS

J. E. Church and James C. Marr

This is a continuation of the report on Improvement in snow-survey apparatus in the Proceedings of the Western Interstate Snow-Survey Conference at Pasadena, California, January 31, 1936, published in the Transactions of the American Geophysical Union, 1936 (pp. 550-557).

Simplicity, universality, and durability are still being sought and urged upon designers and makers of instruments. Because of the need of efficiency under hardship conditions, price is still considered secondary.

Reemphasis--The following points should be reemphasized:

(1) The key of the driving wrench (Fig. 1) must have a right-angled shoulder to furnish sufficient bearing for the weight of the surveyor in driving the sampler through crusts or hard

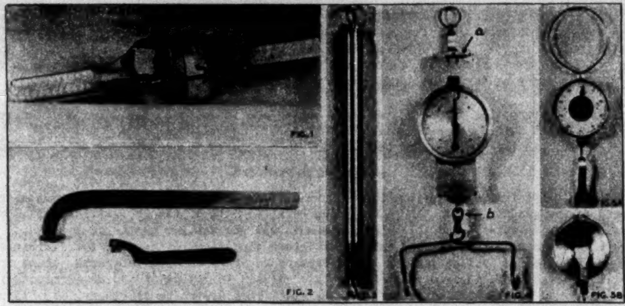

FIG. 1—PORTION OF DRIVING WRENCH SHOWING STEEL KEY [CORNER SHOULD BE SQUARE, NOT ROUNDED OFF AS AT PRESENT, TO PREVENT OCCASIONAL RIDING OUT OF SLOT—HOWEVER, ENDS OF KEY SHOULD BE ROUNDED TO FIT CURVED ENDS OF SLOT THAT MAXIMUM BEARING SURFACE IS OBTAINED]

FIG. 2—SPANNER WRENCHES; STYLE WITH 180° CONTACT AT TOP, OLD STYLE WITH 90° BEARING SURFACE BELOW

FIG. 3—IMPROVED SCALE, BUREAU OF AGRICULTURAL ENGINEERING, 1936, WITH GRADUATIONS ON INNER CYLINDER

FIG. 4—MT. ROSE SPRING-BALANCE AS IMPROVED BY LEUPOLD VOLPEL AND CO., SHOWING (a) LOCKING CLAMP TO PREVENT ADJUSTMENT-SCREW FROM TURNING WHILE SPRING-BALANCE IS CARRIED AND (b) SWIVEL-LINK TO AFFORD GREATER MOBILITY FOR SAMPLER WHILE BEING WEIGHED AND TO PREVENT INTERNAL TORSION IN SCALE

FIG. 5—PARSHALL SCALE, FRONT VIEW (A) READY FOR WEIGHING, AND REAR VIEW (B) FOLDED FOR CARRYING IN POCKET

snow. The curved shoulder recently proposed causes the key to act like a ski and depress the wall of the tube. James C. Marr suggests that the shoulder be made in the form of a hook to grasp the wall of the sampler and that the cross-sectional contour of this shoulder be made convex to fit the curve at the bottom of the slot.

The use of holes in place of slots would accomplish no advantage and would deprive the surveyor of two necessities, namely, observing the rise of the core and cleaning the sampler.

(2) The slots should not be staggered. Such staggering causes confusion and groping in reading the scale on the sampler-tube. Staggering of the sections has been permitted in order to equalize distortion in the sampler-tube caused during manufacture. It is believed that this distortion can readily be eliminated without undue expense.

(3) The temper of the cutter should be so adjusted as to avoid both undue bending of the teeth on one hand or excessive breaking on the other. The metal should in no case be brittle.

(4) The bulging of the cutter has now been reduced to small proportions. Any bulging should be accompanied by gentle contours to avoid catching in the snow, as is the case in the couplings.

(5) Spanner-wrenches must be used to unscrew the sections of the sampler, and holes must be provided in the couplings for their insertion. Wrenches with a curve of 180° will grasp the couplings more securely and with less risk of tearing the holes than will the usual wrench spanning only 90° (Fig. 2).

Anti-seize compounds still fail to give full lubrication of joints. Because of the tendency of duralumin to seize duralumin, R. C. Farrow has suggested the use of a brass washer between the lips of the couplings to prevent seizure at this point. Tests should be made to see whether the threads are not also points of seizure. Consolidation between them has occurred. However, the threads have this advantage: They retain the coating of anti-seize compound better than the smooth ends of the couplings.

The anti-seize compound can best be carried in a "Shinola" can, whose broad surface and special opening device make the lubricant readily accessible, particularly when it loses its plasticity because of cold.

(6) Color should be rubbed into the depressions of the graduations and figures on the sampler-tube to increase their visibility. The lack of contrast makes legibility uncertain, particularly in twilight, and the bright surface of the tube adds to eye-strain.

Temperature-effects with duralumin--Duralumin has won such favor because of its lightness and probable durability that the possibility of snow-adhesion has caused deep concern. Its rapid conductivity of heat and cold as compared with steel may be the cause.

Much difficulty has arisen during the mid-winter surveys, in some cases with steel samplers and frequently with duralumin. Unfortunately the survey-party did not have both steel and duralumin samplers at the crucial times. On the one occasion when both metals were provided for comparative tests, adhesion did not occur. To guide in further observation, the following report of experiences for the present year has been provided by Philip S. Cowgill, Asistant Engineer of the Sierra Pacific Power Company, in charge of field-parties in Nevada Cooperative Snow-Surveys, at Reno, Nevada:

"Herewith my comments on the new U.S.B.A.E. snow-sampling tubes. One of these sets was used on the survey of courses in the vicinity of Independence Lake about March 1, 1937. On the way in, an attempt was made to sample the Sage Hen Creek Course which is on the south side of the Creek on the northern slope of the hill at about 6500 feet elevation. The weather on this day was rather cold with a raw wind. The snow lay in alternate layers of crust and powder with about three inches of powder on the surface. It was found that after the sampler was driven down about ten inches, the core froze in the tube and driving was exceedingly difficult. With a snow depth of about five feet, cores of more than two feet could not be obtained. After an hour of fruitless work the attempt was abandoned.

"The following day the Independence Creek Course was sampled. This Course is on an open flat with slight slope and only a few trees. Here the same difficulty was encountered although the day was comparatively warm. It required nearly three hours to take 19 samples and cores were poor. The cores were very difficult to remove from the sampler.

"The following day the Independence Lake Course was measured. This Course lies on the northern side of a steep hill, elevation about 8200 feet. It is partly through fair-sized timber and partly in an open glade. The day was very cold with considerable wind and frequent snow-flurries. The first few points yielded 10-inch to 15-inch cores with depths of seven to eight feet. The driving was exceedingly difficult and such cores as were obtained were extremely hard to remove. After the core appeared to be out, a close inspection showed a layer of ice perhaps one-eighth of an inch thick all around the tube for the full length of the core. After about a dozen attempts a fire was built and the tube heated to remove the ice-layer. The tube was heated for the entire length used, but care was taken not to heat it sufficiently to injure the metal. It could be readily handled with bare hands at all times. After the ice had melted and the water run out, the tube was further warmed to dry it, after which it was left lying in the snow for a few minutes until cold. The next trial resulted in easy driving with an almost perfect core at the first attempt. Thereafter it was found that by driving the sampler down as rapidly as possible, excellent cores could be obtained at nearly every attempt and cores could be shaken out of the tube very readily. After finishing the course the first points, where the difficult driving had been encountered, were resampled with no difficulty experienced and excellent cores obtained. That night the ends of the tubes were warmed over the chimney of an ordinary kerosene lamp and a very thin coat of paraffin was applied to the inside of the joints.

"The following day the Sage Hen Creek Course was again sampled. This day was very warm, the snow-surface being wet before noon. This time the driving was found to be easy and excellent cores were obtained with no difficulty- except that cores had a tendency to drop out of the cutter while withdrawing the sampler from the hole. No difficulty was experienced in removing cores.

"On all courses the snow lay in alternate layers of ice-crust and powder. The water-content was rather high, densities being about 35 per cent.

"At the present time I can offer no explanation for the cause of the core freezing to the sampler nor of why warming the tube overcame this difficulty if this was the case, nor can I state positively that warming the tube was what overcame the trouble.

"A few days later the Boca and Truckee courses were sampled, three different sets being used for purposes of comparison. Set No. 1 was the U.S.B.A.E. tube as issued. Set No. 2 was the U.S.B.A.E. tube lightly shellaced on the inside, and set No. 3 was a shellaced steel tube of the type commonly used in this locality. The day was very warm and bright and the surface of the snow very wet. No difference could be detected in sampling or in results obtained with the different samplers. However, the U.S.B.A.E. sets showed a greater tendency to drop cores out of the cutter than did the old-type set. This, of course, is due to the fact that these cutters were ground out on the inside to the Mt. Rose standard, thus reducing the width of the shoulder. Another fault of these sets seems to be that they have too much flare on the outside of the cutter, leaving a shoulder so wide that it is apt to catch on crust when withdrawing the sampler.

"On all courses measured it was found that the only sure way to obtain good cores was to drive the sampler down as rapidly as possible. Admittedly this is dangerous practice in so far as cutters are concerned, but it was felt better to risk injury to the cutter than to fail to get good samples. I believe that the necessity for fast driving was due to some peculiar condition of the snow rather than to the type of tube used, as others who were using steel tubes had the same experience.

"On the next trip it is planned to continue observations and try to determine so far as possible whether or not the new tubes will prove satisfactory for local conditions. Thus far it appears that the only advantage is ease of transportation, but this one feature is sufficient to offset a considerable number of disadvantages, particularly on the longer, more difficult trips."

A report was made by Forest-Ranger L. E. McKenzie, Lamoille, Nevada, that the new duralumin spring-balance staff was very unsatisfactory because snow frequently adhered to its point, thus making carrying and reinsertion difficult.

The aluminum cover of the field-notebook should be insulated against frosting the fingers by an exterior of canvas or other cloth.

A project has now been organized to test snow-samples, of both steel and duralumin, under all conditions of weather and snow throughout this coming winter. A test will also be made of the staff. The effects of shellac and paraffin on both metals will be further tested. The difficulty will be to obtain accurate and detailed observations by such snow-surveyors as are resident in the snow-fields.

Progress in improvements

(1) Aluminating or anoiding--A process, called aluminating or anoiding, has now been perfected for hardening the surface of aluminum metals. This has been used very successfully on snow-samplers to prevent oxidation and discoloration of the hands. The same process could be applied to the spring-balances and staffs also.

(2) Removable cutters: (a) Expansion and shrinkage--The search for a detachable cutter has ended successfully after some eliminations. The practice of forcing cutters into the tube by pressure prevented easy removal and reinsertion. The use of expansion of the duralumin by moderate heat to insert the cutter seemed attractive, for repeated expansion of the metal to at least a half-dozen times seemed to leave no permanent increase in diameter. However, the cutter could not be removed by this method, for it also expanded under the heat applied to the duralumin and the difference in the rate of expansion of the two metals was too small to make withdrawal of the cutter possible without the use of force. Such force can easily be applied in the shop, but not in the field, where the emergency operation must be performed. The carrying of an extra cutter-section seemed an unnecessary expense and physical burden.

(b) Threads--At the suggestion of W. W. McLaughlin, an attempt was made to use threads and screw the cutter into place. The following design was worked out successfully by Carl Elges and Jack Ryan: A steel section of approximately 1-1/2 inches was inserted into the end of the duralumin tube to provide a durable base for fine threads, which also were cut into the collar of the cutter. There seems to be no risk of the cutter becoming unscrewed during driving. Rather, adhesion through rusting may occur unless lubricant or a special spanner-wrench is employed. Field-use of this cutter revealed no difficulty in driving or obtaining satisfactory cores because of the additional shoulder caused by the insertion of the steel section.

(c) Solder--A search for solder to unite steel to duralumin has recently attained full success. An inquiry for "Alusol," referred to in the last report, revealed another solder "Alcoa T," suggested in the following letter from R. B. Derr of the Aluminum Research Laboratories, Aluminum Company of America, at New Kensington, Pennsylvania, on April 26, 1937:

> "I have your letter of April 19 addressed to Mr. Dix and concerning the fastening of cutters to snow-samplers by means of soldering.
>
> "First you inquire about 'Allulsol' solder. I believe you refer to an English composition which has received some publicity in the past several years, which is spelled 'Alusol.' This solder is made by the Coventry Aluminum Engineering Products Company, Coventry, England. We examined this material some time ago and found it to be typical of other commercial solders

containing tin and zinc. If you wish to try this material, you can no doubt obtain a sample from the above address.

"We produce a solder-flux under the name of 'Alcoa A' and a solder 'Alcoa T' (formerly XOO) which are suited for many soldering applications. Of course, soldered joints are less stable than welded joints and are not recommended where they may be subjected to severe corrosion. The solder and flux may be used with the same practices employed for other metals. The solder-iron is satisfactory for thin sections and the main requirements are that of employing a hot well-tinned iron and slow movement of the iron so that the metal and flux are heated to the operating temperature as the solder is flowed into the joint. Do not rub the iron back and forth through the flux.

"Torch-soldering or immersion in a solder-bath are generally more satisfactory methods because they permit better control of temperature. When employing a torch the flame is applied close to the joint but not in contact with the flux, and the solder is flowed onto the joint as the flux begins to fume. For dip-soldering, the fluxed and assembled joint is immersed in the solder bath heated to between 650 and 700° F.

"We are arranging to forward you samples of our 'Alcoa A' flux and 'Alcoa T' solder. If you should have any difficulty with their application, we would be glad to know about it."

Frederick Herz and Jack T. Ryan made various tests of this solder. It was found possible to solder the steel cutter firmly into the duralumin tube at temperatures of 200° C or 392° F. This temperature wrought no harm to the duralumin and could be procured and controlled by holding the end of the sampler over hot coals or even over a smoky blaze. The one necessary precaution was to prevent the sampler from touching the coals or being held in the flames. Smoke had no evil effect on the solder. Thus the old method of soldering is again restored in its simplicity and cheapness. The only addition to the former tools will be an emery cloth.

There will be no need of using candles for this purpose and subjecting the solder to the possible injurious effects of candle smoke or grease. The readily available wood fire can easily be controlled. A test of "Alusol" will be made when a sample is obtained.

(3) Variable lengths of sampler-sections--The increase in number of snow-cabins and storage-facilities for sampler-equipment near the snow-courses has made possible the use of sections corresponding to the approximate depth of the local snow-field. The original sampler was especially long to adapt it to the deep snow-fields in the Sierra Nevada. The absence of couplings made the construction of the sampler cheaper and its driving easier. Special lengths of ten feet are now being requested by the Foresters in Utah. However, ease of carrying and replacement or addition of needed sections will prevent the abandonment of standardized lengths except under special circumstances.

(4) Spring-balances: (a) Tubular or cylindrical balances--The United States Bureau of Agricultural Engineering has made further changes in the tubular balance but without essential elimination of defects (Fig. 3).

In an attempt to prevent the entry of snow or water into the balance, the vertical slot and projecting pointer have been eliminated and the scale of inches has been placed on the inner tube. The lower edge of the outer tube thus becomes the pointer against which to read the scale of inches as it is drawn downward. It thus becomes necessary to lean over to read the scale. Furthermore, the masking of the upper part of the scale creates difficulty in reading to half inches and the necessary inversion of the entire scale from downwards to upwards causes confusion. The difficulty of reading to half inches could be corrected by cutting away a portion of the bottom of the outer tube and stretching a wire across the aperature as a pointer. Or preferably an arrow could be projected from the side wall.

However, this corrective effort would be nullified by the ability of the inner tube to revolve freely within the outer. Thus even if the outer tube bore some indication of front from back, the face of the inner tube could not be controlled. "It would play hide and seek with the observer," suggests Ralph L. Parshall, "like a woodpecker on the trunk of a tree."

Another annoyance is the use of the open hook for hanging the cradle. The ease of attaching and removing the cradle is greatly offset by the frequent loss of the cradle when carrying the balance along the snow-course.

Despite the attempt to prevent the entrance of snow or water, the freezing of moisture on the inner tube when drawn out occasionally clogs the instrument. Such freezing has been reported by Dean George D. Clyde. The heat-conductivity of the duralumin may be a factor in the adhesion of moisture.

In one respect a large improvement has been attained. The tubes are of much heavier tubing than before and thus will more readily resist denting and resulting friction of sliding parts.

The previous friction between the cylinders has also been greatly reduced by providing three guide-projections at the top of the inner cylinder and confining the friction mainly to them. Thus, when under tension, the instrument consistently records the same weight within one-half inch, however often the weighing is repeated.

Range and accuracy--This type of spring-balance cannot be adjusted to 0, nor is its range sufficient for all depths of snow. Therefore, an attempt has been made as before to provide two spring-balances, one of 12.5-foot capacity for shallower snows and another of 20-foot capacity for deep snow. Success has not been equal in both.

(1) Balance for 12.5 feet--This shorter type meets all the requirements of range and accuracy imposed for its depth. Two sampler sections of 2-1/2 feet, of which one is the cutter section, or a total of five feet, bring the spring-balance to tension at 0 with a weighing capacity of 135 inches of water. The entire 12-1/2 feet of sampler will reduce the weighing capacity to 86 inches of water. However, this is still sufficient to weigh the entire contents (150 inches) at its possible maximum density of 55 per cent.

The accuracy of this balance is within one inch at all points of the scale. Table 1 provides details.

Table 1--Test of accuracy of U.S. B.A.E. No. 333 spring-balance for 12.5 feet (inches water)

Including sampler for 5 feet			Including sampler for 12.5 feet		
Scale-reading	Computed weight	Divergence	Scale-reading	Computed weight	Divergence
8	8	0	49	49	0
16	16	0	73	73	0
24.5	24	+0.5	81	81	0
32.5	32	+0.5	89	89	0
40.5	40	+0.5	98	97	+1.0
49	48	+1.0	106	105	+1.0
57	56	+1.0	114	113	+1.0
65	64	+1.0	122	121	+1.0
73	72	+1.0	130	129	+1.0

(2) Balance for 20 feet--The balance for 20 feet, unlike its predecessor of 1935, can be brought to tension at 0 with 12-1/2 feet of sampler and thus continue where the balance for 12-1/2 feet leaves off. However, it fails in expected range. Furthermore, the graduations of its scale are two inches apart instead of one inch as in the smaller balance, and so may confuse the surveyor.

At snow-density of 55 per cent, the spring-balance would fail to weigh 20 feet of snow by 44 water-inches or 80 inches of snow. This would be equivalent to 6.7 feet of snow. At 50 per cent snow-density, the spring-balance would fail by 32 water-inches or 5.3 feet of snow. Only by reducing the sampler-length to 17.5 feet can even this depth be weighed by the spring-balance. Even so the density must not exceed 50 per cent. If the snow should have an average density of 55 per cent, only 15 feet of sampler could be used. On this basis, the spring-balance for 20 feet is only 2-1/2 feet superior to the smaller balance of 12.5 feet.

The inaccuracy of the first spring-balance tested may be due to error in length of spring, for the divergence steadily increases.

Tests of three other spring-balances available indicate a close agreement in the tension of their springs, and two of these (Nos. 383 and 386), which were given detailed tests, were found accurate within one-half inch throughout their scale. R. C. Farrow stated that his spring-balance also was good.

Table 2--Test of accuracy of spring-balance for 20 feet (inches water)

Including sampler for 12.5 feet			Including sampler for 20 feet		
Scale-reading	Computed weight	Divergence	Scale-reading	Computed weight	Divergence
9	8	+1.0	26	24	+2.0
18	16	+2.0	35	32	+3.0
27	24	+3.0	43	40	+3.0
36	32	+4.0	53	48	+5.0
45	40	+5.0	62	56	+6.0
53	48	+5.0	70	64	+6.0
62	56	+6.0	79	72	+7.0
71	64	+7.0	88	80	+8.0
80	72	+8.0			

(b) Dial-balances--The Mount Rose spring-balance as manufactured by Leupold and Volpel, Figure 4, now has a friction-clamp on the adjustment-screw and a swivel link above the cradle. The former safeguards adjustment during carrying of the instrument and the latter prevents binding of the weighing bar by twisting of the cradle.

A longer spike is also planned for the lower end of the staff in order to penetrate the ground and thus assure rigid support where the snow is too shallow to provide it.

The Parshall spring-balance (Fig. 5) has recently been designed for compactness, readability, and immunity to moisture. In range, accuracy, and weight, it corresponds approximately to the tubular sampler for 12.5 feet. It similarly lacks adjustment to 0. However, its dial-face and broad scale make it very comfortable to read.

The novel feature of this balance is the substitution of a broad thin hook to insert in the sampler-slot for weighing. It was hoped thereby to eliminate the cradle with its "long horns" and make it possible to fold up the balance "for carrying in the pocket" like a tape. The difficulty with the hook is the balancing of the sampler, especially if the sampler is long, and the greater effort in attaching and detaching it. However, the balance is much more comfortable to carry than others and can be dismantled more readily. The wire handle is for holding during weighing. This naturally is possible only where the sample is relatively light or additional assistance is available.

Another feature is the possible use of rubber or felt where the weighing bar protrudes to seal the case against the entrance of moisture and so possibly to prevent fogging of the glass face. However, fogging has rarely occurred in the case of the Mount Rose spring-balance, whose dial is indirectly exposed to the entrance of humidity, and clogging is practically unknown. Freezing rain or snow cannot enter through the weighing-bar orifice in sufficient quantity to affect the mechanism.

Initial tension is obtained at four inches and oscillation under similar load does not exceed one-half inch. It is planned to use magnetized steel to hold wheel and ratchet in close contact and so prevent play between them. This will make possible the omission of the pin which usually holds the ratchet against the wheel and thereby creates friction.

A swivel link should be provided between the weighing bar and the hook to prevent torsion in the balance due to the swinging of the sampler.

The dial represents 100 inches. However, when reduction is made for the weight of the sampler, the capacity of the balance is sufficient for only snow-cover of 7-1/2 feet at the maximum density of 55 per cent and is insufficient for ten feet at the usual density of 35 per cent.

The relative weight and accuracy of the balance for 12-1/2 feet and the Parshall model are shown in the following Table computed by Mr. Parshall:

Table 3--Comparison of weight and accuracy of the 12.5-foot tubular balance and the Parshall dial-balance (inches water)

Tubular balance for 12.5 feet (B.A.E. No. 348) Necessary for tension 34.4 in. Weight of instrument 16.5 oz.			Parshall dial-balance Necessary for tension 4 in. Weight of instrument 18 oz.		
Dial-reading	Accuracy computed reading	Divergence	Dial-reading	Accuracy computed reading	Divergence
10.2	10.4	-0.2	10.4	10.4	0
18.4	18.6	-0.2	18.9	18.6	+0.3
22.2	22.3	-0.1	22.9	22.3	+0.6
32.5	32.6	-0.1	32.5	32.6	-0.1
51.0	51.2	-0.2	51.1	51.2	-0.1
	Average	-0.16		Average	+0.14

(c) Electrical balances--The following report has been made by Mr. Marr at the urging of the senior writer in order that every possible avenue leading toward improvement of equipment may be pointed out.

TENTATIVE DESIGN OF ELECTRIC WEIGHING SCALE FOR SNOW-SAMPLER

At best the spring-balance is a crude device for determining weight, but when it is subjected to all sorts of weather and abuse, such as are prevalent on snow-survey work, it can be expected to give erratic results as well. In view of these inherent shortcomings of our present weighing scales for snow-sampling equipment, it is expedient that other means for weighing snow-cores be conceived and tried out. As a preliminary step in this direction an electrical scale, illustrated more or less diagrammatically in Figure 6, is suggested.

So far as known, adaptation of the already-developed principle of electrical weighing to snow-survey equipment has not progressed beyond a recognition of the possibility. Several months ago the idea was presented to Walter Fuller, formerly a research worker in the laboratories of General Electric Company, now an employee of the Interior Department, attached to the Boise Public Survey Office. The tentative design, which is the subject of this paper, was prepared by Mr. Fuller. The plan, exactly as presented here, has been submitted to several men of experience in design of snow-survey equipment along with request that it be developed mechanically. The only responses so far received or that we know of, consist of statements pointing out environmental weaknesses in the idea. These will be presently recounted.

The fundamental principle involved in this tentative design is the translation of a force applied to a carbon compression-pile into an electric current, as indicated in the schematic diagram and sketches of Figure 6.

The sketch of the side view in section shows the method of transmitting the force from the weighing platform to the compression-pile through a pair of rigid supporting columns and a compression-spring. Certain refinements, such as the use of transverse corrugations in the sheet of spring-metal and improved methods of mounting, will suggest themselves to the experienced designer, the intent being to show only the general construction of the proposed device.

During operation, the empty snow-sampling tube would be placed on the scale-platform, the push-button depressed, and the electric bridge balanced by rotation of the rheostat. The sampling tube then would be removed from the scale-platform, the sample taken, the tube replaced on the platform, and the meter-reading again noted.

Use of the balanced-bridge type electrical circuit permits self-calibration in the sense that each time a reading is taken the empty tube becomes the reference-weight against which the null-point adjustment is obtained. This minimizes inaccuracies due to disturbing the mechanical assembly in transit, change of battery electromotive force with aging and temperatures, and change of resistance of the component parts.

The two factors having the greatest effect upon accuracy are the linearity of the pressure-resistance characteristic of the compression-pile, and the uniformity of meter-calibrations.

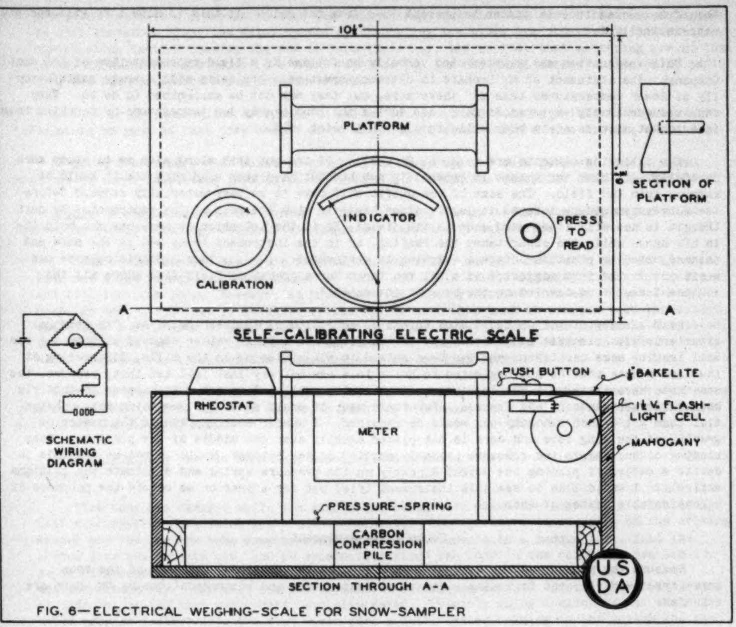
10¼"
PLATFORM
SECTION OF PLATFORM
6"
INDICATOR
PRESS TO READ
CALIBRATION
A
A
SELF-CALIBRATING ELECTRIC SCALE
SCHEMATIC WIRING DIAGRAM
PUSH BUTTON
⅛" BAKELITE
1½ V. FLASH-LIGHT CELL
MAHOGANY
RHEOSTAT
METER
PRESSURE-SPRING
CARBON COMPRESSION PILE
SECTION THROUGH A-A
USDA

FIG. 6—ELECTRICAL WEIGHING-SCALE FOR SNOW-SAMPLER

The principle of using these devices for measurement of fluid height in closed tanks has been used extensively, and it is felt that sufficiently accurate ones are commercially obtainable.

Production-run milliammeters of the type proposed are guaranteed accurate within five per cent of the full scale-rating, and are generally better than this. If necessary for this application, accuracies to within one per cent are obtainable on order.

Flashlight dry-cells, when used in this device, should have a period of service approximating the shelf life, as the use-factor and current drain are both low.

Dr. J. E. Church comments as follows on this device: "Your specifications will be taken to Dr. Roman of the Geophysical Branch of the United States Geological Survey for checking. He has an office here at the University. The large difficulties at once apparent in your plan are the weight of the instrument and the lack of support. It can not be set upon the snow, for the sampler might touch the surface of the snow at some point of its considerable length. Furthermore, the batteries might be subject to low temperatures and burst. Dry batteries in continued cold weather have burst open on Mt. Rose like boiled potatoes. The accuracy of the instrument does not seem to be as great as that of the Mt. Rose spring-balance made by Leupold and Volpel, which also can be set to zero."

M. Leonard, Pacific Division, National Carbon Company, Incorporated, has the following to say about the effects of temperature on dry cells: "Dry cells become inoperative in temperatures lower than 40° above zero and the cell's life is shortened if an attempt is made to use them while the temperature is lower than 40° above. However, the fact that they may be exposed to extreme temperatures does not mean the battery will not operate when the temperature again rises to 40° or higher above. Dry batteries which are used on equipment where extreme temperatures may exist should be packed in some manner to protect them from the cold. If this is done they will operate satisfactorily."

This information was supplemented verbally as follows by a field-representative of the same Company: The statement of M. Leonard is ultraconservative. Dry cells will operate satisfactorily at lower temperatures than 40° above zero, but they may not be guaranteed to do so. They can be successfully employed in this case during any conceivably low temperature by carrying them in a pocket next to one's body while they are not being used.

The following comments are by R. L. Parshall: "I brought this along with me to study more carefully. I think the scheme in general is not bad but have been wondering how it could be carried into the field. The size of the outfit will have to be very materially reduced before the surveyor could be induced to lug it along together with the rest of the equipment. My next thought is how will it be used when in the field? Is it the intention to have one man hold it in his hands while the other takes the reading, or is the instrument to be set in the snow and then adjusted to position before a weighing is performed? . . . . . Your electric balance has merit but in the form suggested is a bit too large for a practical field-size where all the equipment has to be carried on the back of the skier."

L. T. Jessup of the United States Bureau of Agricultural Engineering says: "My personal experience with electric gadgets for use in the field has left me rather opposed to them. I can well imagine some caretaker, who has been snowed in all winter up in the hills, discovering at the last minute that he had neglected to bring in a new battery last fall and that, besides, the wood rats have chewed all the insulation off the wire. Also, I wonder what happens to this rig when water gets into it and freezes. For field-use, it would seem that something more substantial than a 1/4-inch mahogany box would be required. I wonder what happens if the center of gravity of the long tube and core is not placed exactly over the middle of the platform. Does binding occur, and is the pressure properly applied to the spring? Would it not be possible to devise a method of placing the weight directly on the pressure-spring and eliminate the platform entirely? I would like to see this instrument tried out for a year or so before the purchase of a considerable number of them."

Comments on equipment

Because the success of the equipment depends upon the emotional attitude of the snow-surveyors toward it, the following comments by cooperators and recommendations by Mr. Marr are appended:

Provision for use of spanner-wrench in couplings--Harold Conkling, Deputy State Engineer, Sacramento, California, is quoted as follows:

> "We screwed four sections together to make a ten-foot length, smearing the threads as we did so with the special anti-seize grease supplied with this equipment. However, after taking 22 samples, on most of which we had hard going as the tube had to be forced through several ice-layers, we found it impossible to uncouple any of the joints. The tubing, perforce, was carried back down the 6-mile hill in one piece and then had to be strapped to the top of the car. Our route lay through Reno where we had an appointment with Dr. Church and Professor Boardman. Dr. Church was kind enough to have a mechanic in the University machine-shop drill the couplings with 3/16-inch diameter holes, and then by applying spanner-wrenches the tube was uncoupled.
>
> "On our survey next day we carefully wiped off all the anti-seize grease and used a light lubricating oil. However, the tube froze again and it was found impossible to uncouple it with our hands without the aid of tools, and that meant another three miles down hill on skis with an awkward 10-foot length of tubing over one shoulder, a fine way to invite an accident, but fortunately no spills occurred.
>
> "In my mail this morning I find letters from two of our cooperative parties both complaining about this same feature of the tubes. To quote: 'We finished the survey at 5:30 with a 2-hour trip ahead of us to make the shelter-cabin. Two of the lengths of tube uncoupled readily but the other two stuck solid. We worked for over an hour to get these two apart. One man could turn with the driving wrench, but it was impossible to hold the other end. We eventually got it uncoupled by driving a nail in a tree, slipping the slot of one tube over this nail, and, while one man bore down with all his weight, the other twisted with the driving wrench and the tube uncoupled. Because of this delay it was dark before we arrived in the vicinity of the shelter-cabin and in the darkness we missed the turn-off. It took us two hours before we could locate the cabin.
>
> "Comment: Although the writer has not seen the tubes that underwent the above-described

> operation, we have a premonition that the nail through the slot did not do the tube any good. In this instance, also, the delay caused by uncoupling the tubes was undoubtedly one of the contributing factors causing the men to lose their way, and we feel that wandering around lost in the darkness for two hours is a heavy price to pay for the small economy effected by omitting the spanner-wrench holes from the tubes."

By test of new and unused equipment in Boise, Idaho, it was found possible to tighten all tube-joints on hand so that they could not be taken apart without aid of two driving wrenches.

It appears necessary that holes be provided in couplings for this purpose. These holes need not be bored completely through to the inside and it appears desirable that they not be.

Cradle--A complaint with the manner of fastening the hanger to the scale is reported as follows by Harold Conkling, Deputy State Engineer, Sacramento, California:

> "One of the parties has since reported on one or two surveys made with this equipment. They had a lot to say about the number of times the scale-cradle disengaged from the scales and fell into the snow. However, we have remedied this by sending them all a swivel-harness snap, as once the cradle is attached to the scales with this snap it remains fast throughout the entire survey with no possibility of coming loose, and yet, when the survey is completed, the cradle can readily be detached. Other than that, the boys were delighted with the equipment, praising its lightness and convenience of the 30-inch length."

This same complaint has been a general one. There seems to be a further need for this snap because the extra swivel makes it easier to turn the suspended tube in line with the calibrated section of the weighing scale.

Driving wrenches--Harold Conkling, Deputy State Engineer, Sacramento, California, is quoted as follows:

> "The tube was damaged while the sample was being made where the snow had a depth of ten feet with several hard thick ice-crusts underneath. The operator, in standing on the driving wrench and forcing the tube down by straightening his knees with a sudden jerk, felt the wrench give way beneath him, and on examination found the tube in the condition you see it. As we diagnosed the fault, this failure was caused primarily by the rounded end of the driving-wrench key. Had this end been squared off, the tendency to squeeze the tube in and so jump out of the slot would have been eliminated. Possibly using a wider key so that it would project farther into the slot would give a still better bearing on the bottom and also help. Our object in mailing you the tube is so that you may see at first-hand just what has occurred.
>
> "Of course, standing on the driving wrench and alternately bending and straightening the knees with 200 pounds upon it is a drastic way to treat this equipment, but that is the only way it can be forced through the ice-crusts. It takes this even in addition to the turning and grinding so that the equipment must necessarily be designed to 'take it.' You will note that this tube has also been drilled for using the spanner-wrench at the joints. This was necessary in order to uncouple this tube."

It is suggested that the edges of these keys be made to fit exactly the shape of the ends of the slots in the tubes and that they be slightly notched so that they will hook into the tube.

It is thought that possibly a different arrangement than the slots in the tubes and the key in the driving wrench may prove less objectionable and more durable. The thought has occurred to us that the slots may be replaced by a series of round holes and the key be substituted by pins. This arrangement might get away from the tendency of snow to fall into the tube through the slots and a greater bearing surface would be provided for the driving wrench. There is one objection to this suggestion, and that is that such a driving wrench would not be usable with equipment already in use.

Spanner-wrenches--In view of the need which has arisen for a means of uncoupling tube-sections after they have been tightly screwed together, it appears necessary that we provide one or two of these for every set now or later placed in the field.

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Reno, Nevada
U. S. Bureau of Agricultural Engineering (J.C.M.),
Boise, Idaho

ESTABLISHING SNOW-COURSES FOR REPRESENTATIVENESS, PERMANENCE, AND CONTINUITY OF RECORD

George D. Clyde

Introduction--Runoff is derived either directly or indirectly from precipitation. Precipitation occurs in many forms, that is, rain, sleet, snow, hail, dew, frost, and fog. The relationship between the precipitation on and the runoff from a given watershed is complicated by a multitude of factors and, although many attempts have been made to establish a simple relationship between precipitation and runoff, they have met with little success.

In 1894 C. C. Vermuele (Water-supply, Geol. Surv. N.J., vol. 3, 1894) derived various formulas for calculating the annual and monthly runoff of streams, based on certain relationships between retention and runoff. His basic relationship was $F = (R - E)$ in which F = annual runoff in inches, R = annual rainfall in inches, and E = annual retention in inches.

Retention is the amount of rainfall retained permanently or temporarily from the stream and includes mainly seepage, storage, transpiration, evaporation, and plant-consumption.

More recently hydrologists have used the same basic equation, but they have expressed it in different terminology.

$$R = (P - L)$$

$$R = P - \sum(E + t + S + F \pm U)$$

where R = quantity of runoff from the watershed; P = quantity of water precipitated on the watershed; L = quantity of water lost from the watershed; E = quantity of water evaporated from the watershed; T = quantity of water transpired from the watershed; S = quantity of water lost by deep seepage; F = quantity of water consumed by plant-tissue; and U = accumulation or diminution of ground-storage.

This relationship is simple, but the measurement of the terms in it offers many difficulties. To apply this equation in practice would require a quantitative determination of each of the factors.

Precipitation can be measured at any particular point. The evaporation, transpiration, or change in ground-storage can be determined for a specific set of conditions at a given point with fair accuracy. The water lost by deep seepage is more difficult to determine, and that used by plants in building plant-structure is so small that it may be neglected. While the determination of the aforementioned factors is possible at a point, or for a given limited area, it becomes extremely difficult, if not impossible, to determine the precipitation, evaporation, transpiration, and deep seepage over large areas.

Precipitation is the ultimate source of runoff and is one phase of the water-cycle. When precipitation falls as rain, the intensity and duration of the storm, together with the physical condition of the area on which the rain falls, governs the amount and intensity of the runoff. When the precipitation falls as snow, the intensity of the storm is of little importance because the snow accumulates to runoff later during the melting season.

If it is assumed that the same causal factors acting in the same way will produce the same results, a method of indexes may be developed through which the measurement of the causal factors at selected points may be made to indicate the results produced by those causal factors. Such an assumption is the fundamental basis of snow-surveying for predicting stream-flow. Snow-surveying for stream-flow forecasting is not predicated upon a determination of the quantity of water on the watershed at the end of the precipitation-season and the quantitative amount of the losses. Rather it assumes that a normal snow-cover will produce a normal runoff. Snow-courses, therefore, should be located to be representative of average conditions, rather than to measure amounts of water present at any given time.

In those regions where the major portion of the precipitation falls as snow and accumulates to form the storage from which most of the runoff comes it is possible to measure the accumulated snow-cover at the end of the precipitation-season and from such measurements, together with a consideration of other meteorological and the physical conditions on the watershed, to measure the probable water-supply.

The object of this paper is not to discuss the various factors which affect the runoff, but

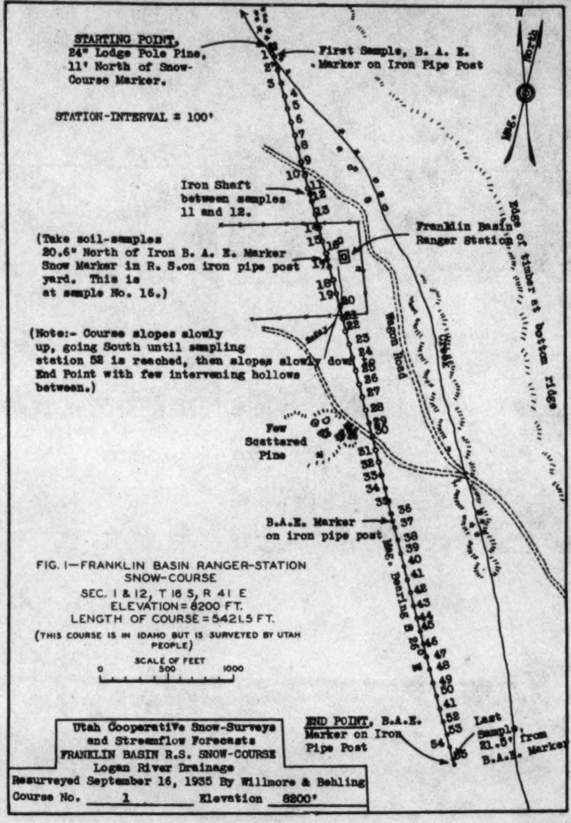
STARTING POINT,
24" Lodge Pole Pine,
11' North of Snow-Course Marker.
First Sample, B. A. E. Marker on Iron Pipe Post
STATION-INTERVAL = 100'
N
North
Mag.
Iron Shaft between samples 11 and 12.
(Take soil-samples 20.6" North of Iron B. A. E. Marker Snow Marker in R. S. on iron pipe post yard. This is at sample No. 16.)
Franklin Basin Ranger Station
Edge of timber at bottom ridge
Wagon Road
Creek
(Note:- Course slopes slowly up, going South until sampling station 58 is reached, then slopes slowly down End Point with few intervening hollows between.)
Few Scattered Pine
B.A.E. Marker on iron pipe post
Mag. Bearing S 26° E
END POINT, B.A.E. Marker on Iron Pipe Post
Last Sample, 21.5' from B.A.E. Marker
SCALE OF FEET
0
500
1000
Utah Cooperative Snow-Surveys and Streamflow Forecasts
FRANKLIN BASIN R.S. SNOW-COURSE
Logan River Drainage
Resurveyed September 16, 1935 By Willmore & Behling
Course No. 1 Elevation 8200'

FIG. 1—FRANKLIN BASIN RANGER-STATION SNOW-COURSE
SEC. 1 & 12, T 16 S, R 41 E
ELEVATION = 8200 FT.
LENGTH OF COURSE = 5421.5 FT.
(THIS COURSE IS IN IDAHO BUT IS SURVEYED BY UTAH PEOPLE)

to point out some precautions that should be taken in the selection of snow-courses over which the basic measurements of the accumulated water-content are made.

Representativeness--A snow-course, to be satisfactory, must furnish data which are indicative of runoff. Where on a given watershed shall the snow-course or courses be located? The first requirement is that it or they shall be representative of the conditions on the watershed. All watersheds are different and, therefore, no specific rule may be laid down which will fit all cases.

The primary requirement for a snow-course is a site having a fairly uniform snow-cover and which is well protected from drifting winds. Such a site can usually be found in a sheltered meadow or a sparcely-timbered flat. Comparatively level open forests, parks, or closed basins furnish the most desirable locations. The course should be as free as possible from large irregularities, steep slopes, boulders, fallen trees, meandering streams, logs, brush, and snowslides. Figure 1 shows a map of the Franklin Basin Snow-Course in Utah, Figure 2 shows photo-

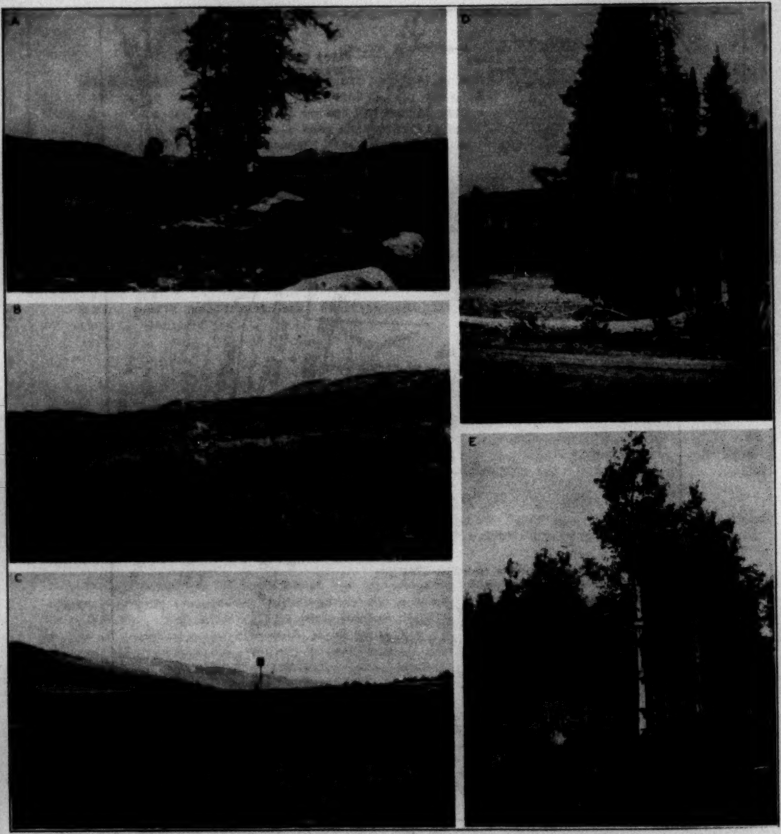

FIG. 2—VIEWS OF FRANKLIN BASIN SNOW-COURSE NO. 1, JUNE 14, 1936
A—LOOKING NORTH AT STARTING POINT B—LOOKING NORTH ALONG SNOW-COURSE SOUTH OF FRANKLIN BASIN RANGER-STATION C—LOOKING SOUTH AT END-POINT D—MILE SIGN 1.8 MILES TO SOUTH E—MILE SIGN 10.1 MILES TO SOUTH AT SOUTH FORK BEAVER MOUNTAIN

graphs of the Course, and Figure 3 shows a profile along the line of observation-points. The Course is covered with a low sagebrush and some willows. The vegetation has been grubbed out for three feet around each observation-point. Figures 4 to 6, inclusive, show similar details for a typical snow-course in Big Cottonwood Canyon near Salt Lake City.

The size of the site is not so important as its exposure, freedom from drifting, and elevation. The exposure should be such as to avoid south slopes where winter melting will take place or areas which are windswept. North slopes are most desirable.

Winds vary in direction and intensity, and falling snow is subject to the smallest wind-movements; therefore, the site should be enclosed by timber or a circle of low hills to reduce

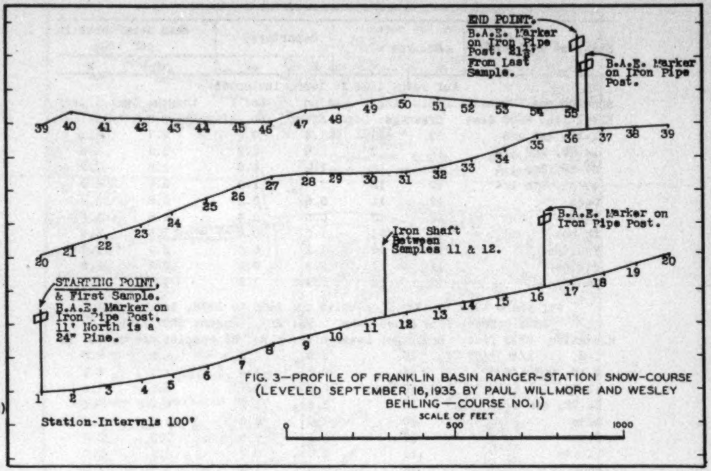

FIG. 3—PROFILE OF FRANKLIN BASIN RANGER-STATION SNOW-COURSE (LEVELED SEPTEMBER 16, 1935 BY PAUL WILLMORE AND WESLEY BEHLING—COURSE NO. 1)

drifting. As we are not concerned with a true catch, it makes little difference whether the course is located on the windward or leeward side of a ridge so long as the individual measurements on the course bear the same relationship to the mean of all measurements on the course each successive year. Such a course is said to be consistent, and to be representative a course must be consistent.

The elevation should be high enough to eliminate melting in winter. This elevation varies widely on different watersheds and some preliminary measurements may be necessary before final selection of snow-course sites. Supplemental courses should be established below the line of melting in winter to indicate the amount of low snow and the extent of melting in winter on the lower slopes. The low snow-courses are particularly valuable in years of heavy precipitation because they furnish a measure of the snow-cover on the low areas and make possible forecasts of early runoff. During years of light snowfall they are of little value because the snow has usually all melted before the end of the precipitation-season. Other conditions being equal, the major snow-courses should be located above the line of melting in winter and as long as this condition is satisfied the more accessible the snow-course the better it is.

How long should a snow-course be? When snow-courses were first laid out in Utah it was thought that the courses should be from one-half to one mile in length with measurements every 100 feet. In many instances locations for courses of that length could not be found and shorter ones were used. Where rough and steep topography was unavoidable it was decided to lay out the courses in the shape of a cross, a triangle or a Y with intervals of 25 to 50 feet between points. Such courses have proven very satisfactory. A study of the effect on the measurement of the mean depth and water-content of snow when certain samples were neglected has been made for four Utah snow-courses and is summarized in Tables 1 and 2. The following is a general summary for the four courses studied:

(1) For all four courses either the odd or even snow-samples may be omitted without departing more than three per cent from the mean water-content of all samples.

(2) Samples consisting of thirds, fourths, sixths, and tenths depart from the mean in the given order with percentages greater than three.

(3) The mean of samples consisting of either the first one-fourth, second one-fourth, third one-fourth, does not follow a general trend, but is related to the topographical features of the snow-course. Figures 1 and 3 show the plan and profile, respectively, of typical courses analyzed.

Table 1--Summary of effects on mean depths and water-contents when certain samples are neglected

Stations included	No. years		Departures D	Departures W	Mean departures in per cent D	Mean departures in per cent W
For years 1928 to 1936, inclusive						
Snow-course: Franklin Basin Ranger Station			No: 1		Length: 5421.5 feet	
Elevation: 8200 feet	Drainage: Logan River			No. of samples now taken: 55		
1-13, 1st 1/4	12	11	1.4	0.9	2.7	4.2
14-26, 2nd 1/4	12	12	1.8	0.8	3.3	2.6
27-39, 3rd 1/4	12	12	1.2	0.8	1.8	3.2
40-52, 4th 1/4	12	12	1.8	1.0	3.6	4.0
Odds	12	11	0.6	0.3	0.9	1.2
Evens	12	12	0.6	0.4	0.8	1.4
Thirds	12	11	1.2	0.6	1.8	2.4
Fourths	12	12	1.2	0.6	2.0	1.8
Sixths	12	11	1.8	0.9	2.7	3.6
Tenths	12	12	2.9	1.5	4.3	6.2
For years 1925 to 1927, inclusive and 1930 to 1936, inclusive						
Snow-course: Tony Grove Lake			No: 2		Length: 3097 feet	
Elevation: 8300 feet	Drainage: Logan River			No. of samples now taken: 32		
1-8, 1st 1/4	10		3.8	1.8	5.3	6.6
9-16, 2nd 1/4	10		2.0	1.4	2.3	4.1
17-24, 3rd 1/4	10		2.3	1.1	3.1	3.8
25-32, 4th 1/4	10		3.6	1.8	4.2	5.1
Odds	10		1.0	0.6	1.3	2.0
Evens	10		1.1	0.6	1.3	2.0
Thirds	10		2.0	0.8	2.5	2.8
Fourths	10		3.0	1.5	3.6	4.9
Sixths	10		4.0	1.9	5.6	6.2
Tenths	10		4.0	2.1	4.8	6.5

Table 2--Summary of effects on mean depths and water-contents when certain samples are neglected

Stations included	No. years	Departures D	Departures W	Mean departures in per cent D	Mean departures in per cent W
For years 1931 to 1936, inclusive					
Snow-course: Silver Lake	No: 16	Length: 1171 feet		Elevation: 8725 feet	
Drainage: Great Salt Lake		No. of samples now taken: 26			
1-6, 1st 1/4	6	0.7	0.5	1.0	2.1
7-12, 2nd 1/4	6	1.1	0.5	1.6	2.0
13-18, 3rd 1/4	6	0.6	0.4	0.9	2.4
19-26, 4th 1/4	6	1.1	0.6	1.8	2.7
Odds	6	0.2+	0.1	0.5	0.4
Evens	6	0.2+	0.1	0.5	0.5
Thirds	6	0.5	0.2+	1.6	1.1
Fourths	6	1.2	0.4	1.4	1.7
Sixths	6	0.6	0.6	0.9	2.6
Tenths	6	1.5	0.4	1.8	2.0
For years 1925 to 1927, inclusive					
Snow-course: Gooseberry Reservoir Site			No: 41	Length: 4848 feet	
Elevation: 8700 feet	Drainage: Price River		No. of samples now taken: 55		
1-13, 1st 1/4	3	3.0	0.9	7.8	5.8
14-26, 2nd 1/4	3	1.3	1.7	3.3	9.6
27-39, 3rd 1/4	3	0.7	0.8	1.7	5.1
40-55, 4th 1/4	3	1.5	0.8	4.3	5.4
Odds	3	1.2	0.5	2.7	2.8
Evens	3	1.2	0.6	2.7	3.0
Thirds	3	0.6	0.4	1.5	2.8
Fourths	3	1.5	0.3	3.3	1.9
Sixths	3	1.0	0.7	2.6	4.4
Tenths	3	2.2	1.0	6.3	6.0

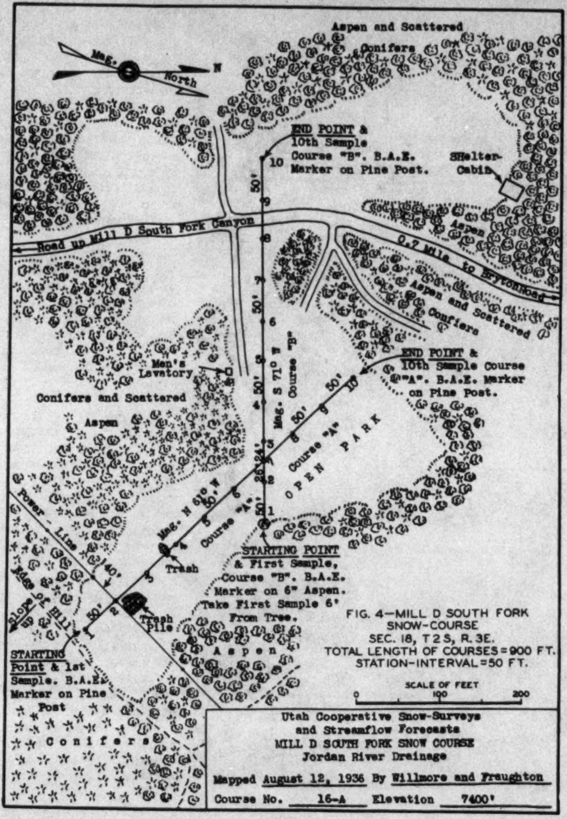
Aspen and Scattered Conifers
Mag. North
N
END POINT & 10th Sample Course "B". B.A.E. Marker on Pine Post.
SHelter-Cabin
10
50'
9
Road up Mill D South Fork Canyon
8
Aspen
0.7 Mile to Brytonroad
7
50'
6
Aspen and Scattered Confiers
5
Men's Lavatory
END POINT & 10th Sample Course "A". B.A.E. Marker on Pine Post.
Mag. S 71° W
Course "B"
4
50'
Conifers and Scattered Aspen
10
50'
9
50'
8
3
Course "A"
OPEN PARK
25.24'
2
Mag. N 61° W
50'
7
6
Course "A"
1
50'
5
4
Power Line
Trash
STARTING POINT & First Sample, Course "B". B.A.E. Marker on 6" Aspen. Take First Sample 6' From Tree.
3
40'
Edge of Slope up Hill
2
50'
Trash Pile
1
Aspen
STARTING Point & 1st Sample. B.A.E. Marker on Pine Post
Conifers
SCALE OF FEET
0
100
200
Utah Cooperative Snow-Surveys
and Streamflow Forecasts
MILL D SOUTH FORK SNOW COURSE
Jordan River Drainage
Mapped August 12, 1936 By Willmore and Fraughton
Course No. 16-A Elevation 7400'

FIG. 4—MILL D SOUTH FORK
SNOW-COURSE
SEC. 18, T 2 S, R. 3E.
TOTAL LENGTH OF COURSES = 900 FT.
STATION-INTERVAL = 50 FT.

(4) A separate study should be made for each course when dropping samples is seriously contemplated.

(5) An analysis of the Utah courses indicates that, in general, if samples are to be dropped it is best to drop them by shortening the course.

The foregoing analysis would indicate that long courses are not necessary and that perhaps relatively short courses of 10 to 20 measurements at 50- to 100-foot intervals with short cross courses would be most desirable. It is more important that the observations be made at the same point every year than to have a large number of observations.

The number of snow-courses required on a given watershed varies. It is impossible to tell in advance the number required. It has been the policy in Utah to establish more courses than was believed necessary in order that a better selection could ultimately be made. On the Logan River Watershed having an area of 220 square miles, there are six snow-courses about 40 miles apart between extremes. A recent analysis of these courses brought out the interesting fact that the three courses on Mt. Logan, when considered alone, gave as good a snow-cover-runoff relationship as the six taken together. This would indicate that one-half of the present courses could be abandoned without sacrifice of accuracy of forecast. The Mt. Logan Snow-Survey can be made in one day while it takes five days to make the measurements over the six courses.

In establishing a snow-survey network it is desirable to locate more courses than finally needed so that a better selection of the most representative ones may be made. Figure 7 shows the present Utah cooperative snow-survey network.

Permanence--Measurements of snow-cover obtained by making snow-surveys are used as indexes of runoff. To be of value as an index they must bear a definite constant relationship to the runoff from the watershed concerned. The measurements of snow-cover, therefore, must be made at the same points year after year for the same reason that the runoff must be measured at the same gaging-station. To insure the measurements being made at the same points each successive year it is necessary that the snow-courses be permanently established and adequately marked. The courses should be accurately mapped and tied to fixed monuments. Profiles should be made of the courses to show the slope and any irregularities in the ground-surface.

The snow-surveying personnel is constantly changing and it is necessary, therefore, to keep an accurate record of snow-course locations so that the snow-cover measurements may continue to be made at the same points.

The maps, profiles, and data-sheets complete for each course should be in the files of the Experiment Station or State Engineer of each State, in the files of the

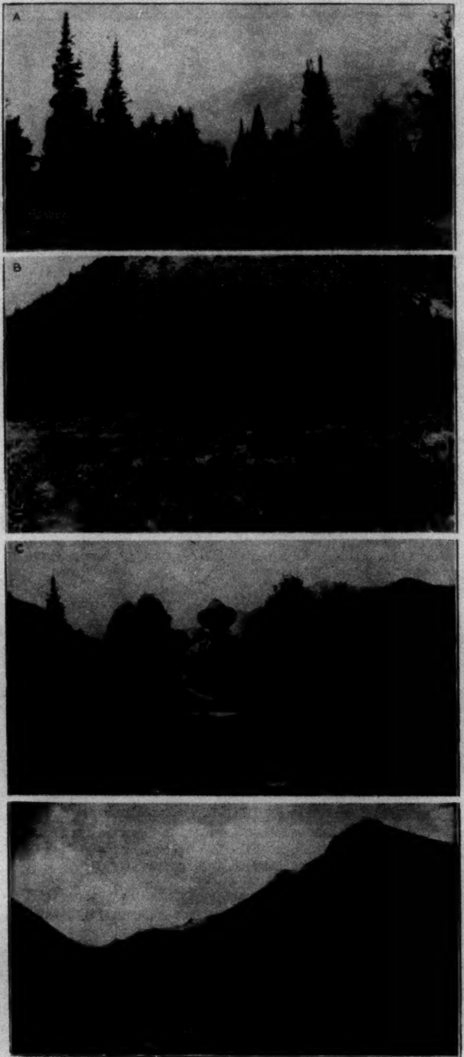

FIG. 5—VIEWS OF MILL D SOUTH FORK SNOW-COURSE NO. 16-A, AUGUST 12, 1936

A—LOOKING NORTHWEST AT END-POINT, COURSE A
B—LOOKING SOUTHEAST AT STARTING POINT, COURSE B
C—LOOKING WEST AT END-POINT, COURSE B
D—LOOKING SOUTH UP SOUTH FORK AT END-POINT, COURSE B

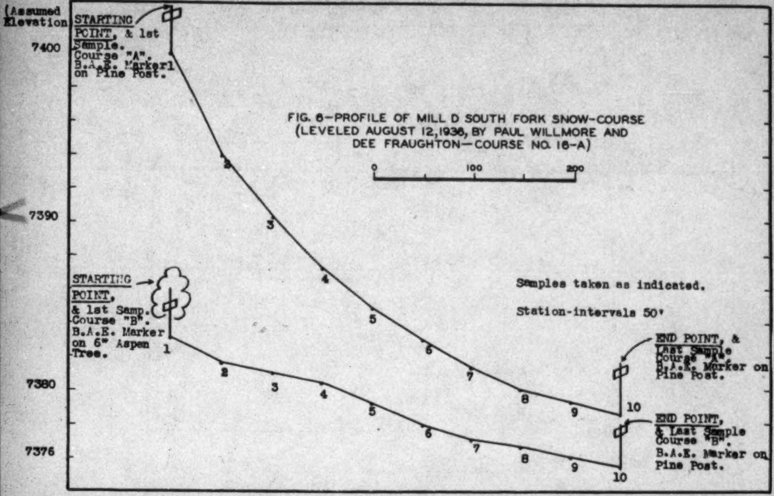

FIG. 8—PROFILE OF MILL D SOUTH FORK SNOW-COURSE (LEVELED AUGUST 12, 1936, BY PAUL WILLMORE AND DEE FRAUGHTON—COURSE NO. 16-A)

Regional Forester and the Forest Supervisor or other cooperating agents, in the files of the man who actually makes the snow-surveys, and in the files of the Federal Coordinator of snow-surveys and stream-flow forecasts, the Bureau of Agricultural Engineering.

The Utah network is now completely mapped and cleared. Figure 8 shows the specifications for the original Utah marker-post. The marker-sign on the post has been changed to show the cooperation between the various Federal and State agencies.

For the purpose of a permanent record, data-sheets should be prepared for each course. These sheets contain pertinent information about each course. The snow-course data-sheets used in the Utah Snow-Survey are reproduced here.

Continuity of records--Records of snow-cover and runoff, to be of value, must be continuous. There must be no missing years. Before forecasts can be made the relationship between snow-cover and runoff must be determined and this relationship will become more constant as the length of the record increases.

At best snow-surveying is difficult and hazardous. Transportation is by snowshoes or skiis, often under extremely trying circumstances. When locating a snow-course it is desirable, therefore, to keep in mind, along with other requirements, its accessibility. Other conditions being equal, the greater the accessibility the more accurate and continuous the record.

The wide-spread character of snow-surveying and the part-time employment it involves will always make it necessary to secure the personnel for making snow-surveys from cooperating agencies. To such personnel, snow-surveying is a side issue and not their main responsibility. Therefore, when conditions are bad or work is pressing, sometimes the snow-surveys are not made. The experience in Utah with the cooperating agencies has been exceptionally good. Few records have been missed, due probably to the fact that nearly all of the courses require not more than two days to make the surveys. Such trips can usually be made between storms which occur so frequently during the early spring. There is no point in establishing a snow-course at some remote high point if a closer site can be located.

There are some courses in the Utah network that should be relocated so as to be more accessible. For example, the Co-op Flat Course out of Cedar City is reached by climbing to the

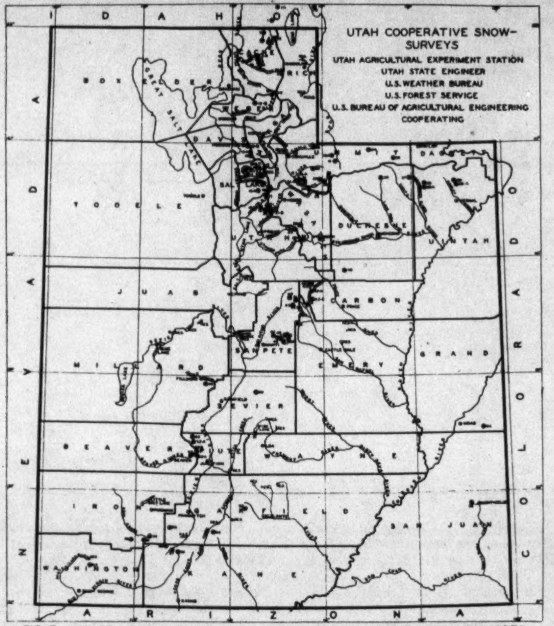
UTAH COOPERATIVE SNOW-SURVEYS
UTAH AGRICULTURAL EXPERIMENT STATION
UTAH STATE ENGINEER
U.S. WEATHER BUREAU
U.S. FOREST SERVICE
U.S. BUREAU OF AGRICULTURAL ENGINEERING
COOPERATING
IDAHO
NEVADA
COLORADO
ARIZONA
BOX ELDER
CACHE
RICH
WEBER
DAVIS
SALT LAKE
GREAT SALT LAKE
TOOELE
UINTAH
DUCHESNE
WASATCH
UTAH
JUAB
CARBON
SANPETE
MILLARD
EMERY
GRAND
SEVIER
BEAVER
PIUTE
WAYNE
IRON
GARFIELD
SAN JUAN
WASHINGTON
KANE

FIG. 7—MAP OF UTAH SHOWING SNOW-COURSE LOCATIONS AND MAIN DRAINAGES

●= LOCATION OF SNOW-COURSES

SCALE OF MILES 0 50 100

top of Kolob Mountain and then about six miles south through rolling topography covered with aspens and open parks. A site at the same elevation and just as desirable could have been chosen five miles closer to Cedar City. To the present course and return is about an 18-hour day out of Cedar City. This is too long. On two occasions the surveyors have had to turn back because of storms before completing the job, whereas if the course had been closer the survey would have been completed. Reasonable accessibility of snow-courses is the best guarantee of continuous records and low-cost surveys.

An ideal location for a snow-course has never been found, yet many snow-courses are well located. Practical considerations are quite often the governing factor in the final snow-course location, but the theoretical factors should always receive very careful study.

Important points to be kept in mind when locating snow-courses may be summarized as follows:

(1) The major courses must be kept above the line of winter-melting. Supplemental courses below the line of winter-melting are desirable to help interpret the abnormal years.

(2) Snow-courses should be located where the snow-cover is uniform and fairly well protected from drifting winds. Comparatively level open forests, parks, or closed basins furnish the most desirable locations. The site should be free from large irregularities, steep slopes, boulders, fallen trees, or meandering streams. If covered with logs and brush it should be cleared around the observation-points.

(3) The courses need not be longer than necessary to average out any ground-surface or

INDEX TO SNOW-COURSES SHOWN ON FIGURE 7

No.	Name and elevation in feet	
CACHE VALLEY STREAMS		
1	Franklin Basin (Idaho)	8200
1A	Emigrant Summit (Idaho)	7700
2	Tony Grove Lake	8200
3	Tony Grove Ranger Station	6250
4	Spring Hollow No. 3	7000
5	Spring Hollow No. 4	8000
6	Mount Logan	9000
7	Smithfield Spring	7000
8	Blacksmith Fork	8400
9	Garden City Summit	8200
12A	Blake Ranger Station	8000
BEAR RIVER		
1A	Emigrant Summit (Idaho)	7700
1B	Slug Creek Divide (Idaho)	7300
9	Garden City Summit	8200
10	Head of Bear River	8600
10A	Goodman Ranch	7900
12	Monte Cristo Ranger Station	9000
OGDEN RIVER		
11A	Huntsville-Wheeler Divide	5775
12	Monte Cristo Ranger Station	9000
12A	Blake Ranger Station	8000
12B	Geertsen Creek	8200
WEBER RIVER		
15	Parley's Canyon Summit	7500
24	Beaver Creek Ranger Station	7500
27	Washington-Long Lake	10300
29	Airway Beacon-Chalk Creek	7000
30	Smith and Morehouse	7600
31	Redden Mine (Upper)	9000
31A	Redden Mine (Lower)	8500
SALT LAKE WATERSHEDS		
13	Parrish Creek	8000
13A	Barnard Creek	8000
13B	Hornet Creek	8100
14	Lamb's Canyon	6600
15	Parley's Canyon Summit	7500
16	Silver Lake	8725
16A	Mill D South Fork	7400
PROVO RIVER AND UTAH LAKE		
17	Dutchman Ranger Station	7500
18	Timpanogos Cave Camp	5500
19	South Fork Ranger Station	6100
20	Camp Altamount	7300
21	Timpanogos Loop Road Divide	8200
21A	Aspen Grove	6900
21B	Y.L.M.I.A. Site	6000
22	Hobble Creek Summit	7300
23	Daniels-Strawberry Summit	8000
24	Beaver Creek Ranger Station	7500
25	Soapstone Ranger Station	7800
26	Trial Lake	9800
27	Washington-Long Lake	10300
28	Lost Lake	9900
STRAWBERRY RESERVOIR		
23	Daniels-Strawberry Summit	8000
33	East Portal	7560
33A	East Portal-Strawberry Divide	8000
NORTH SIDE UINTAH MOUNTAINS		
34	Hewinta Ranger Station	9500
10	Head of Bear River	8600
10A	Goodman Ranch	7900
35	Hole-in-Rock	9150

No.	Name and elevation in feet	
SOUTH SIDE UINTAH MOUNTAINS		
36	Lake Fork Mountain	10500
37	Paradise Park	10500
38	Mosby Mountain No. 1	9700
38A	Mosby Mountain No. 2	9500
39	King's Cabin No. 1	8800
39A	King's Cabin No. 2	8600
40	Indian Canyon	9100
PRICE RIVER		
40	Indian Canyon	9100
41	Gooseberry Reservoir Site	8700
42	Mammoth Ranger Station	8800
42A	Stahley Ranch	7600
42B	Dry Valley Divide	7800
42C	Clear Creek	8150
43	Huntington-Horseshoe	9800
FILLMORE		
49	Pine Creek-Chalk Creek	8500
HUNTINGTON, COTTONWOOD, AND FERRON CR.		
43	Huntington-Horseshoe	9800
48	Seeley Creek Ranger Station No. 1	10000
48A	Seeley Creek Ranger Station No. 2	10000
SAN PITCH RIVER		
42	Mammoth Ranger Station	8800
44	G.B.E.S. Oaks Ranger Station	7550
45	G.B.E.S. Headquarters	8700
46	G.B.E.S. Meadows	10000
47	G.B.E.S. Alpine	10177
SEVIER RIVER		
50	Gooseberry Ranger Station	8400
51	Fish Lake	8700
52	Kimberly Mine (Lower)	8300
52A	Kimberly Mine (Upper)	8900
53	Widstoe-Escalante Summit	9500
54	Bryce Canyon	8000
55	Panquitch Lake	8200
56	Gravel Springs Junction	7500
57	Harris Flat Ranger Station	7700
58	Duck Creek Ranger Station	8561
59	Cedar Breaks	10200
BEAVER		
63	Merchants Valley	8200
63A	Otter's Lake	9300
63B	Big Flat	10000
COAL CREEK		
59	Cedar Breaks	10200
60	Co-Op Flat	9500
61	Webster Flat	9200
VIRGIN RIVER		
56	Gravel Springs Junction	7500
57	Harris Flat Ranger Station	7700
58	Duck Creek Ranger Station	8561
59	Cedar Breaks	10200
60	Co-Op Flat	9500
61	Webster Flat	9200
SANTA CLARA RIVER		
62	Pine Valley	9150
LA SAL AND BLUE MOUNTAINS		
64	La Sal Mountain	8500
65	Buckboard Flat	9000

UTAH
SNOW-COURSE DATA-SHEET

1. NAME OF COURSE: Date:

2. NUMBER OF COURSE: Party:

3. ELEVATION OF COURSE: Weather:

4. LOCATION OF COURSE:

a. Section Township Range

b. Nearest permanent inhabitants at Distance

c. General location (forest, mountain, etc.)

5. DRAINAGE-BASINS:

a. Local Drainage:

b. Main Drainage:

6. DESCRIPTION OF COURSE:

A. a. Topography:

b. Vegetal Cover:

c. Earth Mantle:

d. Approximate depth of soil:

B. a. Length of Main Course No. Samples Sta. Interval

b. Length of Cross Course No. Samples Sta. Interval

7. MARKERS:

a. Number of Markers Established: Kind

b. Location of Markers:

c. Condition of Markers up:

8. CLEARING:

a. Is clearing needed?

b. How much clearing was done

c. Final condition of course

9. SHELTERS:

a. Place of nearest available shelter

b. Distance of available shelter from course

c. Is the available shelter adequate?

d. Needed equipment in shelter

10. SNOW-SAMPLING EQUIPMENT: Owner:

a. Equipment available for course:

1. TUBE: Length Kind Condition No.

2. SCALES: Kind Range of graduation Net Sample No.

3. Field-books:

4. Sling: Condition

5. Field-book cover: Identification No.

6. Maps:

7. Snow-Shoes: Condition

8. Skiis: Condition

9. CUTTER: Condition

PAGE 1 OF FORM FOR RECORDING SNOW-DATA (3/4 SIZE)

2

b. **Equipment needed for courses:**

1. TUBE: Length

2. SCALES: Net capacity

3. CUTTER:

4. (a) Field-book, (b) Book-cover, (c) Maps, (d) Snow-shoes:

5. Other equipment:

c. **Party to whom equipment assigned:**

Address:

11. SNOW-SURVEYS:

a. When are surveys made?

b. Responsible cooperating party:

Address:

c. Party making survey: Address

Assistant: Address

Assistant: Address

d. Time required to make survey in man-days:

Size of party needed:

e. Estimate of cost of making survey:

1. Supplies:

2. Distance traveled by: Car Cost @ 5c per mile $

Horse Cost @ $1 per horse $

Foot

3. Compensation to surveyors:

Chief of Party per day:

Assistants per day:

4. **TOTAL COST** of making survey:

12. COOPERATING PARTIES:

NAME	ADDRESS	COOPERATION

13. REPORTS:

a. Responsible field-agent Address

b. Original notes sent to Address

c. Copies of notes sent to Address

Address

Address

Address

Address

Address

d. Forecast of water-supply made by Address

14. GENERAL:

a. What unusual difficulties are encountered while actually making survey:

b. Earliest date snow melts off of course:

c. When does peak-runoff occur on:

1. Local Drainage:

2. Main Drainage:

PAGE 2 OF FORM FOR RECORDING SNOW-DATA (¾ SIZE)

3

15. REMARKS:

16. SNOW-COURSE RECORDS:

YEAR	JAN.		FEB.		MARCH		APRIL		MAY		Remarks
	Depth in Inches		Depth in Inches		Depth in Inches		Depth in Inches		Depth in Inches		
	Snow	Water	Snow	Water	Snow	Water	Snow	Water	Snow	Water	
1924											
1925											
1926											
1927											
1928											
1929											
1930											
1931											
1932											
1933											
1934											
1935											
1936											
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1942											
1943											
1944											
1945											
1946											
1947											
1948											
1949											
1950											
1951											
1952											
1953											
1954											
1955											

PAGE 3 OF FORM FOR RECORDING SNOW-DATA (¾ SIZE)

drifting irregularities. Usually 20 to 30 stations are sufficient. Courses laid out in form of a cross, a triangle, or a Y have been found very satisfactory. In rough topography satisfactory courses have been established in areas not more than 50 feet in diameter.

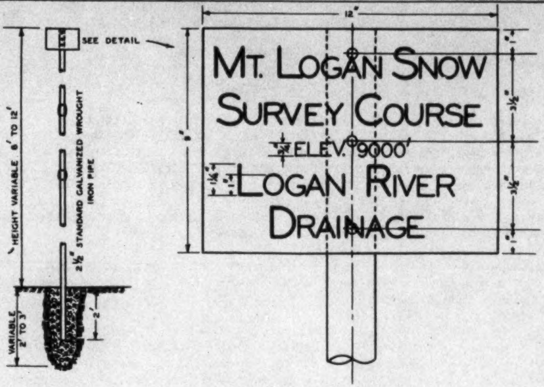


FIG. 8—TYPICAL SNOW-COURSE MARKER AND SIGN

SPECIFICATIONS FOR SNOW-COURSE MARKER SIGNS

1. Marker sign shall be 9 by 12 inches and punched for bolting to marker standards as shown on Figure.
2. Lettering on signs shall be as near the dimensions shown as is possible with standard letter-dies.
3. All signs shall be embossed enamel signs constructed according to specifications of the Forest Service, United States Department of Agriculture, for embossed enamel signs.
4. Lettering for all signs is shown on attached schedule.
5. The color of the back ground shall be orange and the letters black.

SPECIFICATIONS FOR STANDARDS FOR SNOW-SURVEY COURSE MARKERS

1. The standard shall be constructed of 2 1/2-inch galvanized pipe of standard weight.
2. Standards more than 8 feet in length shall consist of at least 2 sections connected with standard sleeves and no section shall exceed 6 feet in length.
3. One end of the standard shall be drilled for 3/8-inch bolts. The top hole shall be 1 inch below top of pipe and other two holes 3 1/2 inches on centers in the same line.
4. The standards shall be set in concrete. Standards 6 feet above the ground shall be set in 2 feet of concrete. All standards more than 6 feet in height shall be set in not less than 3 feet of concrete. The pipe shall be embedded not less than 1 foot in the 2-foot holes and not less than 2 feet in the 3-foot holes.
5. The marker sign shall be bolted to the standard before erection and the sign shall be rotated until it lines up with the forward direction of the course.
6. All standards shall be erected to a vertical position.

(4) To assure permanence of courses they should be accurately mapped, marked, cleared, and fully described in snow-coarse data-sheets. The maps, profiles, and data-sheets should be filed for reference and the courses marked with permanent markers.

(5) Snow-cover records, to be of greatest value, must be continuous and reasonably accessible snow-courses offer the best guarantee of complete records.

Utah Agricultural Experiment Station,
Logan, Utah

SNOWFALL AND RUNOFF IN THE CANADIAN COLUMBIA BASIN: A STUDY TO DETERMINE THE IDEAL LOCATIONS FOR SNOW-SURVEY STATIONS

R. C. Farrow

Introduction

If we ignore the Arctic drainage entirely, snow-surveys in British Columbia would fall into three main divisions: (1) Coastal; (2) Fraser River Drainage; (3) Columbia River Drainage. The first could not be embraced in any single system, consisting, as it does, of numerous more or less parallel rivers rising in the Coast Range and flowing direct to the sea, although in some cases snow-courses could serve two or more streams having contiguous and similar watersheds.

The Fraser River drains the largest area of British Columbia under consideration, and its watershed would form a natural primary unit for a snow-survey system.

The Columbia River and its tributary, the Kootenay, drain most of southern British Columbia, and likewise form a natural unit. The Okanagan River, while also a part of the Columbia System, has its confluence with the main stream in the State of Washington, and, therefore, for our purposes, is treated as a separate basin.

When the Comptroller of Water Rights of British Columbia decided to initiate a system of snow-surveys in 1934, a modest beginning was made with a few courses on the Coast adjacent to Vancouver, and a system for the Okanagan, where water resources are severely taxed and the close regulation of Okanagan Lake would be greatly assisted by forecasts.

The Fraser System as a whole was skipped entirely, as forecasts would be of no immediate utility. Much of its watershed is remote and difficult of access in winter, and the System would be expensive to lay out and maintain.

It was decided to make a start on a system for the Kootenay and main Columbia drainage-systems, both for the benefit of the power companies operating on the Kootenay River and as part of our contribution to the cooperative interstate snow-surveys in the United States of America. With the inception of the Grand Coulee and Bonneville projects, the matter of Columbia River runoff became of vital importance.

The Columbia and its tributaries in British Columbia drain an area of about 40,000 square miles (see Fig. 1). The last gaging-section on the Canadian side of the boundary is at Trail. The mean monthly flow here is in excess of 71,000 cubic feet a second; the maximum recorded flow is 312,000 cubic feet a second, and the minimum is 9600 cubic feet a second.

The initial problem

In forecasting the runoff of most large streams it is usually possible to forecast for its principal tributaries and then combine the results for the main stream. This greatly simplifies both the strategic location of snow-courses and the subsequent forecasting.

In the case of the British Columbia portion of the Columbia River Drainage-System, however, the problem is not entirely one of combining the effects of its tributaries. The East and West forks of the Kootenay can be treated as separate basins; also the Lardeau and Duncan basins as Kootenay tributaries; but the main Columbia from its source at Columbia Lake around the Big Bend right down to its confluence with the Kootenay has no big feeders. The volume of runoff at Revelstoke is about eight times that at Golden, and at Trail about 16 times that at Golden. This enormous increase in flow is due to the numerous short small streams which drain the snow-fields of the Rockies and Selkirks. Only the Canoe River, which joins the Columbia at the Big Bend has a basin of sufficient size to warrant its own snow-course (No. 9). The Kicking Horse and Illecillewaet rivers each probably have a greater flow, but both drain very limited basins.

The problem, therefore, resolved itself into finding locations for courses representative enough to be related to the Columbia itself, at each of its three main gaging-points, Golden, Revelstoke, and Trail, and at the two Kootenay gaging-stations, Wardner and Glade.

Three obvious locations suggested themselves and courses were accordingly laid out at these points.

In sampling the initial Columbia-Kootenay courses I noted with surprise the general uni-

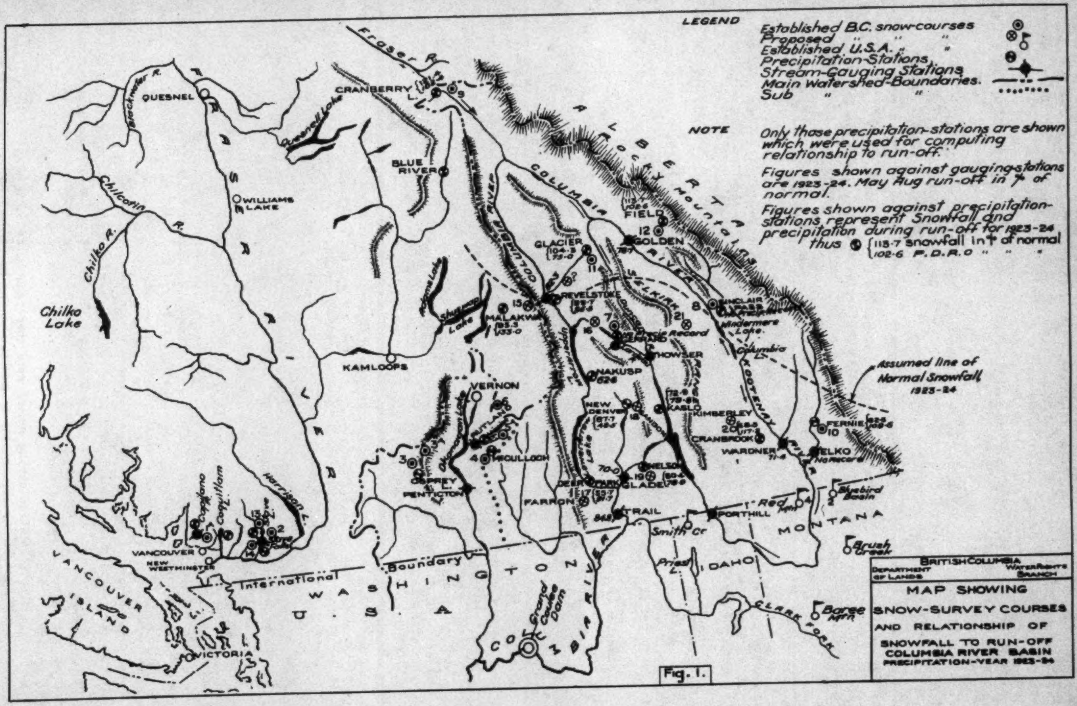

LEGEND
Established B.C. snow-courses
Proposed " " "
Established U.S.A. " "
Precipitation-Stations
Stream-Gauging Stations
Main Watershed-Boundaries.
Sub " "
NOTE
Only those precipitation-stations are shown which were used for computing relationship to run-off.
Figures shown against gauging-stations are 1923-24. May Aug run-off in % of normal.
Figures shown against precipitation-stations represent Snowfall and precipitation during run-off for 1923-24
thus {115.7 snowfall in % of normal
102.6 P.D.R.O " " "
BRITISH COLUMBIA
DEPARTMENT OF LANDS
WATER RIGHTS BRANCH
MAP SHOWING
SNOW-SURVEY COURSES
AND RELATIONSHIP OF
SNOWFALL TO RUN-OFF
COLUMBIA RIVER BASIN
PRECIPITATION-YEAR 1923-24
Assumed line of Normal Snowfall 1923-24
ALBERTA
Rocky Mountains
FRASER RIVER
Fraser R.
COLUMBIA RIVER
KOOTENAY RIVER
SELKIRK
Quesnell Lake
Blackwater R.
Chilcotin R.
Chilko R.
Chilko Lake
QUESNEL
WILLIAMS LAKE
CRANBERRY L.
BLUE RIVER
KAMLOOPS
Shuswap Lake
Adams Lake
MALAKWA
REVELSTOKE
GLACIER
FIELD
GOLDEN
SINCLAIR PASS
Windermere Lake
Columbia L.
Upper Arrow L.
NAKUSP
NEW DENVER
KASLO
HOWSER
KIMBERLEY
CRANBROOK
WARDNER
FERNIE
ELKO
NELSON
GLADE
DEER PARK
FARRON
TRAIL
PORTHILL
VERNON
Okanagan Lake
McCULLOCH
OSPREY L.
PENTICTON
Harrison L.
Capilano
Coquitlam
VANCOUVER
NEW WESTMINSTER
VICTORIA
VANCOUVER ISLAND
International Boundary
WASHINGTON
U.S.A.
MONTANA
IDAHO
Priest L.
Smith Cr
Red Mtn
Bluebird Basin
Brush Creek
Baree Mtn
CLARK FORK
Grand Coulee Dam

Fig. 1.

formity of the snow-density at widely-separated points; differences generally could be accounted for by variations in depth. In view of the varying influences which had acted on the snow since it fell, it seemed probable that the newly-fallen snow must have been even more uniform in density over wide areas. In order to further check up this seeming uniformity, I took occasional samplings as I travelled about in order to check the density, and, in general, found the same uniformity.

This suggested a method of approach, in selecting likely strategic localities for snow-courses, by trying to establish a relationship between the snowfall recorded at existing precipitation-stations and the runoff of the Columbia at Golden, Revelstoke, and Trail, and the Kootenay at Wardner and Glade.

In view of the difficulties usually encountered, and the abortive results usually obtained in attempting such a comparison by any but the most complex methods, it was started as a somewhat forelorn hope.

Part I--Relationship of snowfall to runoff at Golden

Data available--The snowfall-data gathered at the regular precipitation-stations of the Meteorological Service of Canada are obtained in this way: A number of boards are laid on the ground in flat sheltered positions adjacent to the rain-gage. The snow-depth is measured in inches and tenths with a rule each day, or sometimes twice a day in heavy storms; as soon as the measurements are taken, the boards are swept clean again; the mean of the measurements on the various boards is taken as the day's snowfall at the station. Any rain during the months of snowfall is, of course, recorded in the ordinary rain-gage. Both are recorded separately, and the snow then combined with any rain, for total precipitation for the day; the snow-depth being divided by ten to reduce it to water standard.

Since the arbitrarily assumed ten per cent density might or might not represent the truth, it was decided to express all data as percentages of normal, which would make the results relatively comparable by reducing them to a least common denominator, and any error from this source in any one year could be ignored, if the apparent regional uniformity of density was a fact. It was further assumed that density would probably be proportionately the same from year to year.

Much information was tabulated and studied, only to be abandoned, and many false starts were made before anything like a systematic analysis was evolved; the supporting computations and tabulations, therefore, are very voluminous and need form no part of this paper.

The first study was made last year for the runoff at Golden. The precipitation-stations finally used, after much weeding out, and their lengths of record are as follows: Fernie, 20 years; Cranberry Lake, 20 years; Field, 12 years; Glacier, 22 years; Golden, 22 years. The gaging-station at Golden on the Columbia and at Wardner on the Kootenay had a common period of record of 21 years.

It was unfortunate that Field had only a 12-year precipitation-record, since this proved to be one of the most useful stations, and its use involved computing two normals for each of the other stations, one for their common period of record and the other for comparison with Field.

Preliminary studies--A study of runoff-data for both the Columbia and Kootenay rivers indicated that the period of high flow attributable largely to melting snow was from May to August, inclusive.

The precipitation-data of the various stations for each year of record was divided into "snowfall" and "precipitation during runoff." Snowfall included all precipitation from November to April, inclusive, since any rain falling on the snowpack would be absorbed into it and increase the water-content. (Where "snowfall" or "snow" are referred to hereafter, it is in this broader sense, unless the context clearly indicates otherwise.) The only exception to the above is for the month of November--in some years its precipitation was mostly in the form of snow, in others there was considerable rainfall. No rain, therefore, was included unless it followed a period of snowfall apparently sufficient to hold it in storage, or unless followed by freezing temperatures sufficient to hold it in the ground in storage. Precipitation during runoff included all precipitation from May to August, inclusive. Anything falling in September and October was ignored entirely, since it would probably be largely ineffective in producing runoff.

Snowfall and precipitation during runoff were then reduced to percentages of normal for each year--in the case of the latter both by months and for the period May to August.

The runoff of May to August of the Columbia at Golden and the Kootenay at Wardner were likewise tabulated for the same period or periods of record as the precipitation-data, and reduced to percentages of normal. They were also reduced to "inches on the drainage-area" for direct quantitative comparison with precipitation in inches. This comparison was of little direct use, but was sometimes of assistance when studying discordancies in the percentages of normal in occasional years.

The yearly percentages of normal of snowfall and precipitation during runoff for each precipitation-station were then plotted graphically against the percentages of normal of runoff at the appropriate gaging-station (see Fig. 2). These graphs at once disclosed that there was a certain parallelism between snowfall and runoff for some precipitation-stations, but not for others. On the other hand, the trace of precipitation during runoff in most years showed little or no relationship to runoff. This will be discussed later under its own heading.

The data for those stations showing little or no conformity to runoff were discarded.

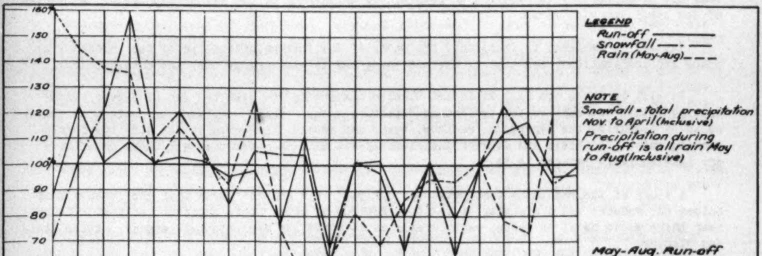
As mentioned before, five precipitation-stations seemed worthy of further study, namely, Glacier, Field, Fernie, Golden, and Cranberry Lake, the first three showing the best graphs.

It was noticed that various stations appeared to be more or less complementary to various others--abnormal years at one corresponding to subnormal years at another. This suggested bringing the data for the different stations together in various combinations, and comparing these with runoff.

Studying the various implications of the five different graphs simultaneously became too confusing, so percentages of normal of snowfall for each of the precipitation-stations and for the averages of their various combinations were, therefore, tabulated and listed against the percentages of normal of runoff; percentage-departures of runoff from snowfall were computed for each station and certain combinations of stations for each year. Other combinations quite obviously would not work and departures, therefore, were not computed for these.

Final analysis--Finally, a statistical analysis was made of these departures. The data for the five individual stations and ten different combinations of their data entered this analysis. The fact that Field only had 12 years of record as compared with 20 for the other four stations necessitated working out five more cases than would otherwise have been necessary.

Before starting the tabulation and analyses, it was noticed that the year 1923-24 was abnormal, in that the departure of runoff from snowfall was excessive for all stations and all combinations of stations, varying from 13 to 31 per cent--in one case being over four times the mean departure for the period. Being so far out of harmony with most other departures in the various series, it unduly weighted the normals and departures, and was, therefore, discarded. The reason for its discordance became apparent later on and will be discussed in its proper place.



NOTE
Snowfall - total precipitation Nov. to April (Inclusive)
Precipitation during run-off is all rain May to Aug (Inclusive)

May-Aug. Run-off Columbia River at Golden, related to precipitation-data for Glacier, all in % of normal

Fig. 2

The analysis for those precipitation-stations and their combinations showing the greatest conformity to the runoff of the Columbia at Golden is shown in Table 1.

Table 1--Comparison of runoff of Columbia River at Golden with combination of snowfall-data at indicated stations

[Note--Period of record, 1924-25 to 1935-36, eleven years; snowfall (unweighted means of per cent of normal); A = Field and Glacier; B = Field, Glacier, and Golden; C = Field, Glacier, and Cranberry Lake; D = Field, Glacier, and Fernie; E = Field, Glacier, Golden, and Fernie]

Station or group	Per cent departure of runoff from snowfall						No. of years in which per cent departure lies between				
	Aggregate	Maximum	Minimum	Mean	Modal group	Median	0-10	10-15	15-20	20-25	25+
Field	90.9	20.4	0.2	8.3	5 to 8 for 6	7.2	8	2	..	1	..
Glacier	72.2	14.8	0.1	6.6	0 to 5 for 5	7.0	8	3	..	..	..
Fernie	207.4	44.2	1.2	17.3	12 to 21 for 5	17.9	3	2	2	3	1
A	56.5	12.1	1.3	5.1	1 to 4 for 6	3.8	10	1	..	..	..
B	90.8	18.0	2.4	8.3	3 to 6 for 5	5.8	8	1	2	..	..
C	87.9	14.4	0.5	8.0	7 to 12 for 7	9.5	8	3	0	..	..
D	76.7	18.3	1.3	7.0	6 to 12 for 5	6.7	7	3	1	..	..
E	110.7	19.6	2.1	10.1	5 to 10 for 6	9.6	7	1	3	..	..

Looking at the map it might be wondered why any attempt was made to relate the snowfall of such remote points as Cranberry Lake and Fernie to the runoff of the Columbia River at Golden. In the first place, it was desired to trace any parallelism which might exist between the various stations. In the second place, in so far as Cranberry Lake is concerned, it is the only precipitation-station in the Columbia Basin below Golden until Revelstoke is reached and therefore presented the only data available which might even remotely represent conditions in the Big Bend Area and which would, therefore, be needed for correlating to Revelstoke. Third, Fernie was introduced in order to try to confirm any similarity of conditions between the adjacent upper Columbia and upper Kootenay basins. Its use was suggested when it was found that a preliminary normal for Snow-Course No. 8 in Sinclair Pass, computed from the runoff of the Columbia at Golden, only varied by about five per cent from the normal computed from the Kootenay at Wardner.

Interpretation of Table 1--Of the individual precipitation-stations the only ones shown are Field and Glacier, outstandingly the closest in conformity to runoff, and Fernie as representing the upper Kootenay. Cranberry Lake showed slightly more conformity than Fernie and Golden slightly less.

The snowfall-data of Glacier and Field, individually, shows a remarkable conformity to runoff. A comparative examination of their yearly percentages of normal shows that, in many years, they are complementary in relation to runoff, the deficiency of one being balanced by the excess of the other and vice versa.

Table 1 is designed to facilitate the study of the interrelationships of the various stations and combinations, and clearly reveals where and to what degree they are complementary.

It will be noted how well Field and Glacier combine in "A" with ten out of eleven years falling within the zero to ten percentage-departure group. Their complementary nature is indicated by comparing the aggregate, maximum, mean, and median departures of "A" with the corresponding values for Field and Glacier individually--it will be noted that all these departures are substantially reduced in "A."

A study of the remaining combinations, "B," "C," "D," and "E" shows that the inclusion of Golden has reduced the conformity of all combinations of which it is a factor, so that a course near there would be of no value, particularly as it would lie approximately midway between Field and Glacier.

Cranberry Lake does not combine well with the other stations, although it is to a slight extent complementary to Field and Glacier. While the conformity of its snowfall to runoff is poor, it combines with Field and Glacier without seriously lessening their individual conformity, indicating that a certain general relationship exists. It does not warrant the use of Course No. 9 in its vicinity in attempting to forecast the runoff at Golden, but does suggest that it may be valuable as an outlier course applicable to points further down the River.

Fernie, poor in the individual conformity of its data, is somewhat similar to Cranberry Lake, in that it does combine to some extent with Field and Glacier, and it is interesting to note that for the longer period of record, when there were no data for Field, the mean of the snowfall-data for Glacier and Fernie showed the greatest conformity to runoff, which seems to indicate a general uniformity of snowfall-conditions between the upper Columbia and upper Kootenay.

The foregoing shows, so far as unweighted percentages of normal are concerned, that a mean between Field and Glacier snowfall-data conforms closer to runoff of the Columbia River at Golden than any other combination of the various precipitation-stations that have been tried, which would indicate that snow-courses near these points should furnish a reliable index to runoff.

For the 11-year period of common record, the departure of runoff from the mean of their percentages of normal of snowfall for percentage-departures 0 to 5, 5 to 10, and 10 to 15 was six years, four years, and one year, respectively. It was thought that an even closer relationship might be established by weighting the snowfall of each according to the percentage of the drainage-area which it might be assumed to represent.

In order to apportion the watershed between the two stations, the total Columbia watershed tributary to Golden was delineated on a map. The mean precipitation (in inches) between Glacier and Field was then taken and the corresponding isohyetal line was identified on our precipitation-map, and this line transferred to the watershed-map as the dividing line between the areas tributary, respectively, to Glacier and to Field. These areas were then measured by planimeter, and each expressed as a percentage of the whole.

These area-percentages were used to weight the snowfall of Field and Glacier and a further statistical analysis was made. The weighting, however, had very little effect, though giving slightly less conformity to runoff than when unweighted means were used.

Last year Snow-Courses Nos. 11 and 12 were laid out near Glacier and Field, respectively. In the meantime, the mechanics of forecasting were gone through for the first time for the Columbia at Golden, using the second year's sampling for Course No. 8 in Sinclair Pass, based on a normal computed from the runoff. The error in forecast using only this one course was 11.5 per cent. It was intended, therefore, to use Nos. 8, 11, and 12 for forecasting the runoff at Golden; this idea was modified somewhat as the result of further studies, and a fourth course will also be used.

Part II--Relationship of snowfall to runoff at Revelstoke

Data available--The next step was to extend the study to include the gaging-station on the Columbia River at Revelstoke. Only two more precipitation-stations were usable. The data considered were for Field (12 years), Glacier (21 years), Cranberry Lake (21 years), Revelstoke (21 years), and Malakwa (21 years).

The hydrometric data for Revelstoke, although going back to 1915, unfortunately had a six-year break in the record. However, a study of runoff by months for the common periods of record for Golden and Revelstoke showed that they could be interrelated without introducing a probable error much in excess of the probable error inherent in the snowfall-data with which it was to be compared. Monthly coefficients were, therefore, computed and the runoff at Revelstoke for the missing period was worked up from the Golden runoff-data. Since these computed data, when compared with snowfall, appeared to be in harmony with the general relationship for the balance of the period of record, evidently no serious error was introduced.

This study deliberately overlaps on the series previously analyzed and applicable to Golden, as it was desired to trace not only the relationship to runoff at Revelstoke, but also the general relationship between widely-separated precipitation-stations over the basin as a whole.

Analysis--The final analyses are all shown in Tables 2, 3, and 4. As there were records available for only 12 years for Field and for 20 for all other stations, two separate analyses were made. Table 2 is the final result including Field for the 12-year record and Table 3 excluding Field for the 20-year period.

The year 1923-24, as in the case of the analysis for Golden, showed a wide discordance between snowfall-data for all stations and runoff at Revelstoke. It was, therefore, excluded from the 12-year record, but was included in the analysis of the longer 20-year record. It was, however, eliminated from a secondary final tabulation (Table 4) for comparison with the 12-year sum-

Table 2--Final comparison for 12 years 1924-1936, runoff Columbia River at Revelstoke in per cent departure from snowfall at Glacier, Cranberry Lake, Field, Revelstoke, and Malakwa, and averages of various combinations

[Indications for averaged stations are : A_c = Glacier, Cranberry Lake, and Field; B = Glacier and Field; C_c = Glacier, Cranberry Lake, Field, and Revelstoke; D = Glacier, Field, and Revelstoke; E_c = Glacier, Cranberry Lake, Field, Revelstoke, and Malakwa; F = Glacier, Field, Revelstoke, and Malakwa; G = Field, Revelstoke, and Malakwa; Gl = Revelstoke and Malakwa]

Precipitation-station or average	Per cent departure						No. of years in which per cent lies between					Total years
	Aggregate	Maximum	Minimum	Mean	Modal group	Median	0-10	10-15	15-20	20-25	25+	
Glacier	112.3	23.0	0.3	9.4	5 to 10 for 5	9.3	8	2	0	2	..	12
Cranberry Lake	328.3	61.5	2.9	27.4	20 to 30 for 4	23.8	2	2	0	2	6	12
Field	106.3	20.8	0.0	8.9	1 to 6 for 4	8.4	7	2	2	1	..	12
Revelstoke	140.2	32.1	1.7	11.7	10 to 16 for 5	11.3	5	4	2	0	1	12
Malakwa	185.6	39.0	0.9	15.5	3 to 6 for 5	8.4	6	2	0	1	3	12
A_c	170.1	23.5	4.1	14.2	14 to 19 for 5	15.9	4	2	3	3	0	12
B	85.3	16.2	1.4	7.1	5 to 10 for 6	6.3	10	1	1	0	0	12
C_c	149.2	20.8	0.7	12.4	15 to 20 for 5	14.0	4	2	5	1	0	12
D	89.9	14.9	0.0	7.5	0 to 5 for 5	7.6	8	4	0	0	0	12
E_c	149.1	22.6	2.7	12.4	15 to 20 for 5	13.2	4	2	5	1	0	12
F	106.0	20.9	0.8	8.8	1 to 6 for 5	7.8	7	3	1	1	0	12
G	113.4	27.9	1.4	9.6	4 to 9 for 5	7.7	8	2	0	1	1	12
Gl	136.5	35.5	0.4	11.4	7 to 14 for 5	8.4	7	2	1	0	2	12

Note--Suffix "c" (as in A_c) indicates that combination includes Cranberry Lake.

Table 3--Final comparison for 20 years 1915-1935, runoff Columbia River at Revelstoke in per cent departure from snowfall at Glacier, Cranberry Lake, Revelstoke, and Malakwa, and averages of various combinations

[Indications for averaged stations are: H_c = Glacier and Cranberry Lake; I_c = Glacier, Cranberry Lake, and Revelstoke; J = Glacier and Revelstoke; K_c = Glacier, Cranberry Lake, Revelstoke, and Malakwa; L = Glacier, Revelstoke, and Malakwa; M = Revelstoke and Malakwa; N = Glacier and Malakwa]

Precipitation-station or average	Per cent departure						No. of years in which per cent lies between					Total years
	Aggregate	Maximum	Minimum	Mean	Modal group	Median	0-10	10-15	15-20	20-25	25+	
Glacier	248.9	45.4	0.3	12.44	4 to 10 for 9	9.3	12	2	0	5	1	20
Cranberry Lake	455.7	61.5	0.7	22.80	0 to 6 for 5	21.7	5	3	1	3	8	20
Revelstoke	226.3	32.1	0.5	11.30	0 to 5 for 7	10.9	9	5	4	1	1	20
Malakwa	235.7	39.0	0.9	11.80	0 to 5 for 8	6.0	12	4	0	1	3	20
H_c	308.2	33.3	0.5	15.41	10 to 15 for 6	13.7	6	6	1	3	4	20
I_c	258.9	28.2	1.3	12.94	7 to 15 for 8	11.7	9	2	4	2	3	20
K_c	233.8	25.1	0.3	11.69	20 to 25 for 5	10.6	9	4	1	5	1	20
J	199.0	33.3	0.6	9.95	0 to 5 for 8	7.6	11	4	4	0	1	20
L	195.5	23.6	0.7	9.77	0 to 5 for 9	8.1	11	3	4	2	0	20
M	188.5	35.5	0.4	9.42	0 to 5 for 9	7.9	13	3	2	0	2	20
N	235.8	26.2	1.1	11.79	1 to 5 for 7	8.5	10	2	6	1	1	20

Note--Suffix "c" (as in H_c) indicates that combination includes Cranberry Lake.

mary, and 1935-36, not available when the data were first compiled, was added in, so there still remained a 20-year record.

General deductions--On studying Tables 1, 2, 3, and 4, certain facts come to light, and the following general deductions seem permissible:

(1) That in most years the distribution of snowfall over that portion of the Columbia-Kootenay drainage represented by these precipitation-stations is remarkably uniform. (It may be said here that this uniformity is not so apparent if a quantitative comparison is made, but comes to light when percentages of normal are used, since these reduce the data of different and quantitatively-varying stations to a least common denominator.)

(2) That the snow itself in most years must be remarkably uniform in density over very wide areas.

(3) As a result of the uniformity deduced in (1) and (2), that a surprisingly close agreement can be traced between ordinary precipitation-records of snowfall and the ensuing records of runoff. (This assumes that the total period of snowfall and total period of snow-runoff have been closely identified.)

Uniformity of flow of the Kootenay River--In order to check these deductions from another angle, a comparison was made between the runoff of the Kootenay River at Wardner and at Glade, and also of the Columbia River at Golden, Revelstoke, and Trail.

In the case of the Kootenay, hydrographs were plotted of the runoff at Wardner and at Glade for the four months May to August for their common period of record of 21 years--the same period as that covered by the analyzed precipitation-data (see Fig. 3). These were plotted one beneath the other, and in order to make them readily comparable a vertical scale was used for Wardner three times that of Glade. These hydrographs indicated the great similarity of regimen at the two places, but an exact comparison was rendered difficult by reason of the balancing effect of the intervening expanse of Kootenay Lake, which in most years delayed the high flow recorded in June at Wardner so that July usually became the high month for Glade.

Still on the same sheet, therefore, and using the same time-scale, both flows were plotted as percentages of normal. This at once disclosed a remarkable uniformity in the relationship between the flow at the two points, despite an average increase in volume of nearly four times. This uniformity is indicated by the variation between the percentages of normal of runoff of Kootenay River at Wardner and at Glade. Thus for variations in per cent of normal of 0 to 5, 5 to 10, and 10 to 14, the number of years was 13, 6, and 2, respectively.

Similar hydrographs and percentage-graphs were plotted for the Columbia River at Golden, Revelstoke, and Trail. The variation in their percentages of normal are as follows:

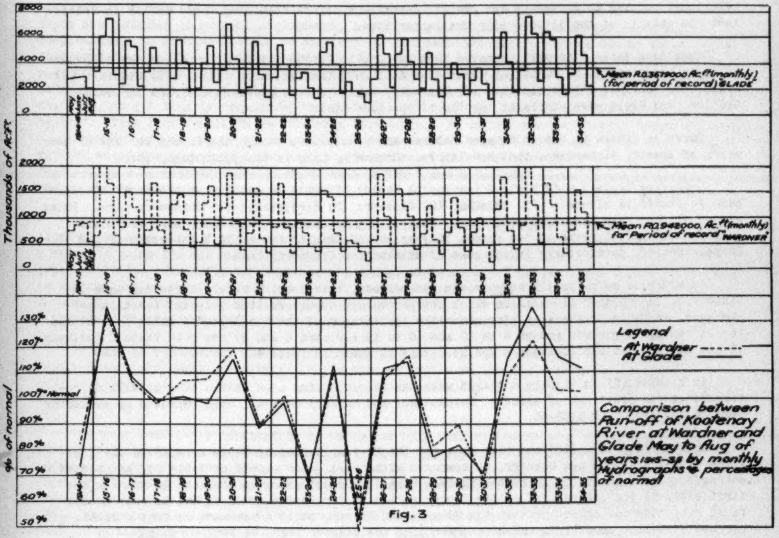


Fig. 3

	Number of years between		
Variation in per cent of normal	Golden and Revelstoke	Revelstoke and Trail	Golden and Trail
0 to 5	9	8	8
5 to 10	8	8	8
10 to 15	4	5	5

Since it is axiomatic that if the flow at widely-separated points on a river (in the case of Wardner and Glade on the Kootenay, points are 300 miles apart, while on the Columbia, Golden, and Revelstoke they are 200 miles apart and Revelstoke and Trail are 175 miles apart) are closely proportional, then the snowfall which produces this runoff must be remarkably uniform both in distribution and density over the entire drainage-area tributary to the two points. Furthermore, the precipitation during runoff must either also be very uniform in distribution or else negligible in effect. Since it appears that early rains in summer throughout this area are much more spotted in occurrence than the snowstorms in winter, it would seem likely that precipitation during runoff-effect will in most years be a negligible factor.

The close relationship between the flow at Wardner and Glade substantiates deductions (1) and (2) above based on the snowfall-runoff ratio.

This flow-relationship is the more remarkable when it is considered that amongst the many tributaries which feed the Kootenay between Wardner and Glade there are the Lardeau and Duncan rivers, which drain a considerable area of the Selkirk Range and flow into the north end of Kootenay Lake, and that their combined flow last year equalled 80 per cent of the flow of the Kootenay at Wardner, which would indicate that this region is subject to the same general uniformity of precipitation. Otherwise their flow would have been sufficient to disturb the Wardner-Glade relationship.

Comparison of Tables 2, 3, and 4--For the purpose of this memorandum it has seemed best to place the cart before the horse, and first draw a general picture of the conditions indicated by the analyses in Tables 2, 3, and 4, and the Wardner-Glade and Golden-Revelstoke-Trail runoff-relationships, and to enumerate the general deductions before examining these Tables in detail lest the details of the latter befog the larger idea.

Examining Table 2 it will be noted that the precipitation-stations listed in the closeness of their relationship to runoff at Revelstoke fall into the following order: (1) Glacier; (2) Field; (3) Malakwa; (4) Revelstoke; (5) Cranberry Lake. In the previous analysis for Golden, Glacier and Field were easily at the top of the list also.

There is little to choose between Malakwa and Revelstoke, though the former has one or two years of greater discordance than Revelstoke. Cranberry Lake is disappointingly poor.

Comparing Table 3 with Table 2 (excluding Field), it will be noted that the order of closeness to runoff is altered: (1) Malakwa; (2) Glacier; (3) Revelstoke; (4) Cranberry Lake. Malakwa and Glacier have exchanged positions. This is due to the fact that there were more, and greater, discordant years in the common 12-year period than in the extra eight years of the 20-year record, particularly in the case of Malakwa and Cranberry Lake.

In order to more readily compare the two periods, therefore, a retabulation was made in Table 4 of the "number of years in which the percentage-departure lies between" (certain percentages) in Table 3; there is also shown the percentages of the total period which fall within the percentage-departure groups 0 to 10 and 10 to 15 (columns 2 and 3) for both Table 2 (columns 10 and 11) and Table 3 (columns 8 and 9). This is shown in Table 4.

If columns (2) to (5) are compared with the corresponding ones in Table 3, it will be noticed that the positions of Glacier, Revelstoke, and Malakwa have all been improved by excluding 1923-24 and including 1935-36.

Columns (8), (9), (10) and (11) show how the 20-year period of Table 3 improves the positions of all stations but Glacier, as compared with the 12-year record of Table 2. As pointed out before, this is due to there having been more discordant years in the last 12 than in the first eight of the period, and in the longer period of record their effect has to some extent faded out. The comparison between the 20-year and 12-year periods was made on that account, and because different deductions might be drawn from the shorter than the longer record.

It is not intended to discuss the 12-year period any further as pertaining to Revelstoke

Table 4--Rearrangement of occurences of percentage-departure in Table 3 to eliminate the discordant year 1923-24 and to include the year 1935-36 for better comparison with Table 2 (Table 2 covers the 12-year period 1924-36, 1923-24 being eliminated and Table 3 covers the 20-year period 1915-35 including 1923-24)

Precipitation-station	Number of years in which per cent departure lies between					Total years	Per cent of total period that departure was below 10 per cent and 15 per cent			
							From Table 3 20 years		From Table 2 12 years	
	0-10	10-15	15-20	20-25	25+		10 o/o	15 o/o	10 o/o	15 o/o
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Glacier	13	2	0	4	1	20	65	75	66	83
Cranberry Lake	5	3	1	3	8	20	25	40	17	33.5
Revelstoke	9	6	3	1	1	20	45	75	41.5	75
Malakwa	13	3	0	1	3	20	65	80	50	66

Note--For example, for Glacier 13 years below 10 per cent is 65 per cent of the 20-year period and for (13 + 2) = 15 years below 15 per cent is 75 per cent of the 20-year period.

runoff. The 20-year period is designed to answer that purpose. The shorter period was worked up only for the purpose of bringing Field into the picture and, in this connection, it will be noticed how remarkably well Field and Glacier combine in the relationship to runoff (see average "B" of Table 2). It will also be noticed in Table 2 what a poor showing Cranberry Lake makes and how its influence adversely affects every combination of which it is a factor (see averages A_c, C_c, and E_c, Table 2).

Relationship of various precipitation-data to runoff of Columbia at Revelstoke--A detailed study of Table 3 shows that in relation to runoff, Malakwa and Glacier take first and second places and are very close to each other in agreement; Revelstoke comes third, whereas Cranberry Lake is the poorest in relationship. It is evident, however, that when the data for these stations are combined in varying arrangement, a station poor in its individual agreement may be complementary to another station or stations so that combined they produce a closer relationship to runoff than two good stations combined. For instance, although Glacier and Malakwa are the best individual stations, yet in "N" of Table 3 they do not combine as well as Revelstoke and Malakwa in "N," which is the best combination of all; and "L," the combination of the three best stations, is not greatly reduced.by the inclusion of Cranberry Lake--by far the poorest station in "K_c". This last result is particularly interesting, as in the shorter 12-year record of Table 2, Cranberry Lake showed up so badly that it was not worth consideration and, therefore, by inference would throw serious doubt on the effectiveness of Snow-Course No. 9 in its vicinity. "K_c" of Table 3, however, clearly shows that Course 9 has a definite place in the network as a whole, and is valuable as an outlier course.

Interpretation of Table 3 as a guide to location of snow-courses--The generally close relationship between some of these precipitation-stations and runoff at Golden and Revelstoke provides a valuable guide for the strategic location of further snow-courses, but their effectiveness, great as it is, can easily be overrated. A casual examination of Tables 2 and 3 might tempt one to assume that courses at Field and Glacier could be used to represent the whole Columbia Basin, especially considering the greater accuracy of snow-surveys as compared to ordinary precipitation-data. Malakwa and Revelstoke are nevertheless obvious locations for new courses.

It must be remembered, however, that many years are apt to occur when certain areas will depart from their usual uniformity. Table 3 shows that even the best precipitation-stations have discordant years. The reason behind these discordancies is, therefore, a fruitful aspect to study.

The year 1923-24 is outstanding as being the only year of the 20-year record in which there were wide discordancies between snowfall and runoff for all the stations so far examined, departures varying from 13 to 39 per cent (see map of Fig. 1). Moreover, the snowfall-runoff ratios for the Kootenay above Wardner showed the same discordancies. Cranberry Lake, Malakwa, Revelstoke, Glacier, Field, and Fernie all showed snowfall about or above normal, yet the runoff of the Columbia at Golden was 78.7 per cent, at Revelstoke 82.3 per cent, and at Trail 84.8 per cent. The Kootenay at Wardner was 71.4 per cent and at Glade 70 per cent. Precipitation during runoff was normal or above for most stations, although a study of this factor by months indicated that it may not have sustained the runoff to the extent that the percentage for the 4-month period indicated. For instance, at Field it was 106.9 per cent of normal for the 4-month period; but by months was 56.9 per cent of normal in May, 100.6 per cent in June, 76.1 per cent in July, and 173 per cent in August. It was largely rainfall in August, therefore, that raised the percentage for the period above normal. Examination of temperatures showed that May and June were unusually warm, so that the 173 per cent of normal rainfall in August probably fell on ground from which the snow had already gone and was, therefore, largely ineffective in its influence on runoff.

It was evident, however, that some far wider cause lay behind the wide-spread discordance, and it seemed logical to assume that it must be lack of snowfall over an extensive part of the drainage-area. To assist in the solution of this problem, the percentages of normal of snowfall, precipitation during runoff, and runoff at the various points were noted on the map of Figure 1.

Looking at the map this area of deficient snowfall might lie at the headwaters of the Kootenay and Columbia. Sinclair Pass precipitation-station, which should indicate whether this was so or not, was only established in 1934. But it seems unlikely that the major storms which produced snowfall at Cranberry Lake 121.4 per cent of normal, at Glacier 104.3 per cent, and at Field 113.7 per cent, could have dissipated themselves to any great extent only a few miles south of Field when Fernie showed a snowfall of 82.5 per cent. Nevertheless, this decline of the snowfall southward was worth following up, so Cranbrook precipitation-data were worked up; it is a far from representative station but follows the general trend to some extent. It showed a snowfall of only 58.5 per cent of normal for 1923-24. The fact that the Kootenay River at Glade at 70 per cent of normal showed little variation from Wardner with 71.4 per cent suggested that the same influence of low snowfall had pertained in the Kootenay Lake Area. It was, therefore, decided to work up a group of precipitation-stations in the Kootenay Lake and Arrow Lake areas so as to try and trace this area of low snowfall. These stations would be required in any case for completing the studies to Trail on the Columbia and Glade on the Kootenay. After the usual weeding-out process, those finally retained and worked up showed the following snowfalls: Nakusp 68 per cent; New Denver 87.7 per cent; Deer Park 55.1 per cent; Nelson 80.4 per cent; and Kaslo 72.9 per cent. These are noted on the map, which now presents a fair picture of the snowfall-runoff situation in 1923-24. An attempt has been made to roughly define a line of "normal" snowfall separating the area of abnormal snow from the area of subnormal. It is represented on the map by the dashed line.

It evidently passed north of Malakwa and very close to Revelstoke, thence across the summit of the Selkirks at about the divide between the Beaver and Duncan rivers, since Glacier to the north shows a snowfall of 104.3 per cent; while the area of the Duncan and Lardeau rivers is evidently in the low-snowfall belt, since their flow has not disturbed the Wardner-Glade runoff ratio. From the summit of the Selkirks this "normal" line is harder to define, but it probably crossed the Columbia Valley near Sinclair Pass and then continued southeasterly passing north of Fernie. This is indicated by the percentages of normal of both rivers. The upper Kootenay near Field probably received a runoff from snow that was about normal, but, as it flowed south into the area of lesser snow, its flow would gradually fall more and more below normal until somewhere in the neighborhood of Cranbrook, from there on remaining at about the same percentage of normal. The Columbia at Golden, showing a higher percentage of normal (78.7 per cent) than the Kootenay at Wardner, evidently had less of its watershed within the area of low snowfall; from Golden to Revelstoke in an area of snowfall above normal its percentage was raised to 82.3 at Revelstoke.

It will be noticed that with the exception of Fernie all the precipitation-stations whose snowfall was discordant with runoff in 1923-24 are in, or very close to, the area of abnormal snowfall.

The results of the study of conditions which obtained in this somewhat abnormal year are quite as valuable as criteria for the location of additional snow-courses, as the general uniformity which is evident in Table 3, and serve as a warning that reliable forecasts cannot be expected without a wide enough distribution of courses to detect abnormal conditions in certain areas when they occur.

It is evident, for instance, that our present courses 8, 10, 11, and 12 at Sinclair Pass, Fernie, Glacier, and Field, respectively, while excellently located in themselves, are insufficient to consistently forecast for the Columbia at Golden and the Kootenay at Wardner, since the large runoff-area of the easterly slope of the Selkirks is not represented. Unfortunately, this area is difficult of access. A course near Kimberly might be effective for its southern portion. Kimberly lies northwest of Cranbrook, is about 600 feet higher, and lies on the lower slope of the Range. Another course on the lower slope of the Selkirks somewhere west of Sinclair Pass is also required. It would be difficult of access, but appears to be necessary. Course No. 8 in Sinclair Pass takes on a new significance.

Complete analyses for Trail on the Columbia and Glade on the Kootenay have not yet been made; but, in view of the comparatively slight variation in the percentages of normal of runoff at different points on both streams, it seems certain that the same degree of uniformity in snowfall persists in this area that is revealed in the analyses for Golden and Revelstoke, and courses can, in consequence, be located with a fair amount of confidence after a more cursory study of the precipitation-data, although it is intended to complete the analysis before actually laying them out.

A study of the map suggests Sandon and Nelson as localities where courses could be strategically located, as also a course west of Deer Park on Lower Arrow Lake. Near Farron on the Kettle Valley Railway would be accessible and is at the summit of the Divide. Somewhere between Malakwa and the summit of the Divide west of Revelstoke is another strategic location for a course that is strongly indicated.

The strong position of Revelstoke in Table 3 suggests the advisability of a course in its vicinity. It might be thought that with a course at Glacier, one also near Revelstoke would be superfluous, but a detailed study of their respective departures shows that Revelstoke is, in fact, a complementary station to Glacier.

The only accessible area east of Revelstoke is up the Illecillewaet Canyon, which is used by the Canadian Pacific Railway. It may be very difficult, however, to find a suitable and protected location on the walls of this deep and precipitous gorge. It is an area notorious for slides in March and has given the Canadian Pacific Railway more trouble in this regard than any other section of its main line.

It is probable that Course 5A on the Mission Creek plateau can be used for Columbia forecasts. It is sited at elevation 6000 in snow-conditions thought to be typical of the summit of the Monashee Range for a considerable distance towards Malakwa.

Additional courses in the Big Bend Area are desirable. But this Area is only accessible with snow-shoes or skii in winter, and would mean a trip of 60 to 90 miles each way, which is quite out of the question. Use of a plane would be the only solution.

Conclusion

Based on the foregoing, therefore, seven new snow-courses will be located and laid out this summer, and perhaps one more, if accessible location can be found. This should complete the Columbia River network in British Columbia, until such time as experience indicates the necessity for changes or additional courses. Location of the new courses is indicated in Table 5.

Table 5--Location of new courses

Course No.	Located at or near	Remarks	Approximate-elevation
			feet
15	Three Valley	Between Malakwa and Summit	3000
16	Ferguson	East of north and Upper Arrow Lake	5000
17	Farron	On K.V.Ry. summit west of Arrow Lake	4000
18	Sandon	Slocan area	3000
19	Nelson		3000
20	Kimberly		3600
21	Horsethief Creek or Toby Creek	West of Wilmer-Columbia Valley	4000+
	Revelstoke[a]	Up Illecillewaet Valley	3000+

[a] This is desirable but it may be difficult to find an accessible location.

Precipitation during runoff--It seems unlikely that this will be a disturbing factor, except perhaps in occasional years, in view of the generally remarkable parallelism between snowfall and runoff. It was examined graphically for several stations and no recognizable influence on runoff was noted (see Fig. 2). It might, however, account for the few discordant years and, when time and opportunity occur, it is intended to combine this factor for the various precipitation-stations and analyze them in the same manner as the snowfall. Since summer rains are far more spotted in occurrence than the snow-storms of winter, the data for different precipitation-stations may well be even more complementary than snowfall has shown itself to be.

Preliminary snow-course normals--The snowfall-data for those precipitation-stations showing a reasonable relationship to runoff can be used to produce a preliminary normal of water-content for new snow-courses in their vicinity, so that a start can be made on the mechanics of forecasting as soon as the first year's sampling is obtained. Since the snowfall-data are in terms of water-content on the basis of a ten per cent density, a normal can be computed by reducing the average snowfall in inches for the period of record in the proportion of (10/density at sampling).

Percentages of normal in hydraulic studies--In passing it is suggested that engineers might make far greater use of percentages of normal in making comparative studies of the runoff of adjacent streams. In the West, particularly, the engineer is all too often faced with a lack of hydrometric data, and often has to extend a short period of record by comparison with the longer one of an adjacent stream, whose regimen is, in his opinion, sufficiently similar.

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STATISTICAL ANALYSIS OF SAMPLING ON SNOW-COURSES

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Two distinct kinds of sampling are involved in locating and measuring every snow-course. First, the snow-course itself is selected to sample snow-conditions on the watershed in question. And, second, the individual points of measurements are located to sample the snow, or more specifically the water-content, along this particular course.

In the first instance the location of the sample (the snow-course) is carefully selected according to more or less standard criteria. Nothing is left to chance. The observer finds such a place as he has in mind and establishes the course. Because of physical limitations, no attempt is made to secure data free of personal bias. As a consequence, statistical analysis is not applicable to this type of sampling. Nor for the purpose intended, that of annual comparison between the same course, would statistical analysis be of any particular value.

In the second instance, that of sampling the snow on a specific course, a field is opened for the application of statistics. The points of measurements along the course are presumably all drawn from a single homogeneous population and, although they are not selected at random, they are obtained at fixed intervals, thus eliminating largely the personal bias of selection. Under these conditions, statistical measures can and should be used as tools by the snow-surveyor to determine whether his course has been chosen properly, whether too many or too few stations are being sampled, and whether or not a single station or even an entire course should be abandoned for reasons not apparent from the raw and unanalyzed data.

The data--To demonstrate the value of analyzing snow-course data statistically, the March 1, 1937, measurements from 55 courses located and maintained by the Bureau of Agricultural Engineering in Colorado and Wyoming were compiled. (These data were supplied through the courtesy of R. A. Parshall, Senior Irrigation Engineer, Bureau of Agricultural Engineering.) Each of these courses samples a given set of conditions and each course was selected with due care by trained personnel. Observations were taken by forest rangers, national-park rangers, local irrigation-interests, and other interested parties. Standard equipment was used throughout and standard instructions were followed on every course. Because of these features, any error due to the human element or to the equipment should be at a minimum within the physical limits encountered and can be ignored in this analysis.

The error with which statistical analysis is concerned is that, and only that, due to improper or inadequate sampling of the snow-courses. This problem might be approached from several angles all involving the normal curve of error. The simplest and most direct procedure, however, is that using the arithmetic average and standard deviation in their most elemental form. These two statistical constants were calculated for the water-content of each course following procedure which can be found in any standard text-book on statistics.

Were enough samples taken on each snow-course?--To ascertain whether or not enough samples were taken on any one course it was arbitrarily decided that the results were satisfactory if the error of sampling was within plus or minus ten per cent of the average water-content for that course. Meaning that if other courses were established to sample the snow in the same locality the average water-content for them in 19 out of 20 instances should not vary due to chance alone more than plus or minus ten per cent from the average of the first course established. A less rigorous test would be to increase this acceptable limit of error and more rigorous test to decrease it. The odds of 19 out of 20 were used because, according to common practice in the use of the normal curve of error, plus or minus two standard errors of the average is considered as an acceptable range and with this range the odds are 19 to 20 that the sampling error will not exceed established acceptable limits due to chance variation alone. With the standard deviation calculated directly and the standard error taken as five per cent of the average (as explained, the acceptable limit of error is ten per cent of the average which equals two standard errors; therefore, one standard error equals five per cent of the average), the following formula can be used to estimate the adequacy of the sampling: $SE_a = SD/\sqrt{N}$, where SE_a = standard error of the average, SD = standard deviation, and N = number of observations.

For example, on March 1, 1937, the Berthoud Pass, Colorado, Snow-Course had an average water-content of 9.31 inches. The standard deviation of the observations taken on the Course was 2.26 inches. Taking this standard deviation as a valid estimate of the true one for the population sampled, how many measurements should have been taken to secure an accuracy of ten per cent? Substituting in the above formula: $0.446 = 2.26/\sqrt{N}$, $\sqrt{N} = 2.26/0.446$, and $N = 23.5$.

Actually 21 observations were taken, necessitating an increase of only three stations to insure an average accuracy within ten per cent in 19 out of 20 trials.

Similar calculations were made for each of the 55 snow-courses and in 22 instances it was found that more measurements were taken than was needed to obtain an average water-content figure accurate within the limits selected. On 12 courses less than ten observations would have been sufficient. Obviously, on these 22 courses more work was being done in sampling snow-conditions than was necessary.

On the remaining 33 courses insufficient measurements were taken to insure an accuracy within ten per cent of average water-content of the snow. On 21 of these courses less than a total of 100 observations would have been necessary, but on the remaining 12 from 106 to 2173 stations would have been necessary to secure an average water-content figure accurate within the specified limit of sampling error.

The records from these courses requiring more than the present number of observations were examined to ascertain the possible cause of the inadequate sampling. It was readily apparent that whenever the snow on the course was drifted the normal number of stations was insufficient to secure statistically sound data. On some courses trees and brush near a few points of measurement introduced sufficient error to invalidate the average water-content figure obtained.

In addition to the analysis of the March 1 snow-course data, the May 1, 1937, data for 27 of these same courses were analyzed in the same manner. Of these 27 courses the adequacy of sampling on 21 of them was the same on May 1 as on March 1. On four courses where the sampling was adequate in March from two to eight additional stations were needed in May. And on the remaining two courses sampling was adequate in March but more than 20 additional stations were needed in May. This comparison brings out that there is little change in accuracy secured on a respective course from month to month although some variations may be expected. Because the average water-content is within a given limit of error one month there is an indication but no absolute assurance that it will remain so at a later period of measurement.

What is the application of this analysis?--Information secured from statistical analysis of snow-courses has broad application. First, it can be readily determined whether a snow-course is sampled sufficiently to secure an average accurate within a given established limit. For a course found to be sampled satisfactorily by the present number of stations, no change is necessary. If the course appears to be over-sampled, the number of stations can be reduced to the absolute minimum indicated by the analysis. For the most part, however, the labor involved in measuring a course once it is reached by the surveyor is so small that reduction of the number of stations is hardly justifiable.

For a course inadequately sampled, statistical analysis should be used as a guide toward revision. For example, assume that the record of a poorly sampled course is examined and two or three measurements appear to be out of line. This course should be examined in the field and the stations where the questionable measurements were taken examined in particular. It may be found that these stations are influenced unduly by brush or trees or that some other readily observable factor will justify relocation or dropping the questionable stations from the course. Ordinarily a few justifiable changes on an originally well-located course should be sufficient to bring the average water-content figure within acceptable limits of error. If the variation between stations on a course appears unexplainable from field-observations and the original field-sheets show that snow drifts were present, there may be no solution except to abandon the course in favor of one more satisfactorily located. Or if the course cannot be relocated enough new stations should be added to the present course to bring the average water-content figure with acceptable limits of error. The number of new stations needed can be calculated as previously explained, remembering, of course, that after new stations are added new statistical constants should be determined and the required number of observations recalculated to ascertain whether or not the difficulties have been solved.

Some caution should be used in applying statistical methods. It may be found that snow accumulates on a given course in a significantly different manner from year to year, depending upon prevailing winds and other meteorological elements. If this is true, varying numbers of stations to insure a given accuracy will be required in different years. The only way to avoid this difficulty is to analyze separately the snow-course data taken in the various years and compare the results obtained. This comparison should influence the number of stations which should be measured to secure accurate results over a period of time. Under all circumstances, however, sound judgment is a necessary counterpart of statistical analysis. Statistics is a guide and tool only and the snow-surveyor familiar with his own snow-course knows how well and within what limitations it can be applied.

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ACCURACY OF AN INDIVIDUAL SAMPLE IN A SNOW-COURSE

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Why and how much does the water-content of a particular sample in a snow-course vary from year to year in relation to the mean water-content of the course?

In the process of the study of this variation, the mean water-content for a course was obtained for each year. The percentage of the mean for each year for each sample was determined by dividing the mean water-content of the course into the water-content of each sample. These data were tabulated under the headings "Scale" for water-content and "Percentage of mean" for the percentage of the mean water-content.

After the above data were compiled, they were plotted upon coordinate paper with the percentage of the mean as the ordinate and the sample number as the abscissa. The graph is graduated above and below 100 per cent, which is the mean of all the samples for each year. This gives the relation of the water-content of each sample to the average or mean water-content of the course for that year.

The center of gravity of the "Percentage of mean" was then computed and plotted, after which a dotted line was drawn connecting the centers of gravity of the consecutive samples of the snow-course. Where the ordinate-points for any sample for a period of years are scattered with a wide spread, the sample is not reliable. On the other hand, if the points are all within a close range of each other, the sample is reliable and of value to the course. In this way, the graph gives a fairly accurate indication of the value and reliability of each individual sample.

The data compiled were taken from the Tahoe-Truckee River Basins and include the earliest snow-survey records, up to and including the year 1936. Data were computed and graphed for the following courses: Mount Rose-Contact Pass; Truckee No. 2; Daggets Pass; Lake Lucile; Rubicon No. 1; Granite Peak; Weber Peak (Weber No. 1); Weber Lake (Weber No. 2); Upper Truckee; Marlette Lake No. 1; Marlette Lake No. 2; and Marlette Lake No. 3.

Field-trips were taken and a study of the field-conditions was made in an effort to determine why one sample should be above or below the mean water-content of the course. While it is apparent that more field-studies should be made, it was found that the various conditions of sunlight, wind, slope of the ground, positions of the trees, etc., have very definite effects upon the water-content of the samples. These conditions will be discussed in more detail later.

On Tuesday, April 13, 1937, a field-trip was made to the Truckee No. 2 Course. At that time there was about the same amount of snow on the ground as there was at the time of the April 1 survey. The reason for selecting this Course was due to its great variation between the center of gravity of the samples and for this reason it was believed that it would afford the best opportunity to determine what factors influenced the variation in water-content from year to year.

The following data regarding the amount of sunlight, slope of the ground, position of the trees, direction of the wind, etc., were obtained. For convenience, the percentage of the mean is listed in Table 1, so an idea may be obtained of how the percentage reacted to various conditions.

Table 1--Accuracy of individual samples in a snow-course

Sample number	Percentage of Sun	Slope of ground	Percentage of mean	Sample number	Percentage of Sun	Slope of ground	Percentage of mean
1	90	2:1	120	12	70	7:1	70
2	100	1.5:1	145	13	70	5:1	105
3	90	4:1	115	14	95	7:1	110
4	95	3.5:1	120	15	90	6:1	80
5	95	3:1	110	16	70	7:1	65
6	95	3:1	120	17	20	5:1	55
7	75	0	105	18	35	4:1	100
8	95	6:1	105	19	10	0	50
9	90	6:1	115	20	40	0	90
10	90	6:1	110	21	40	10:1	95
11	80	11:1	100				

Sample-point No. 2 has a little steeper slope than sample-points 1, 3, and 4. A small ridge 30 feet west of No. 2 and in the direction of the prevailing wind is more apt to cause snow to drift at that point of sampling than it is at the other three sample points. Therefore, it would have more of a water-content than samples 1, 3, and 4.

Sample-point No. 5 is affected by the ring of dripping of a 12-inch fir-tree eight feet northwest of it under which the snow had melted to a small extent. The point is on the outer edge of that ring and that, in our opinion, is why the sample is ten per cent lower than samples on either side of the same slope and exposure to the Sun.

Sample-points 7 and 8 are affected by a group of three pines under somewhat similar circumstances as sample-point 5. Sample 9 increases ten per cent, in our opinion, because there are no trees affecting it. Of course, if the sample were farther in toward the tree, it would be affected to a greater extent.

Sample-point 12 is also affected by the melting ring beneath a tree. Samples 11 and 13, with practically the same conditions of sunlight, slope, and drifting, are higher because of no adverse effect from trees.

Sample-points 15, 16, and 17 are in the midst of a group of firs. During dry years there is no snow for a recording at these points. If there were no snow on the samples, the only information that could be used for an indication would be the date at which the snow disappeared. This information is rather difficult to obtain, so these samples are not of much value in dry years.

In general, if a sample-point is bare, the snow-surveyor should estimate whether the percentage of bare samples on the course compares favorably to the percentage of ground barren of snow on the part of the watershed represented by that particular snow-course. If not, that point should be omitted in computing the mean water-content of the course.

Sample-point 18 is between two groups of fir trees where it is affected by drifting. As drifting varies with the wind and does not increase the snow-content of a watershed, that sample is especially unreliable.

Sample-point 19 is affected by dripping from a large tree.

It is not believed that a sample taken within the ring of dripping from a tree is an average sample. This is due to the fact that at a certain temperature there is not the same amount of melting in the open as there is beneath the tree where the snow is affected by the dripping. In spite of the fact that this dripping occurs only for a relatively short time after storms and then only if it is warm enough to melt the snow, we believe that it is sufficient to affect the reliability and value of the sample.

Thus it can be seen that keeping the sample-points away from trees is an important consideration in choosing a reliable course. On the other hand, at low elevations the only snow that would remain late in the spring would be that under trees, so that any rule laid out would have to be adapted to fit the individual case.

Our results would seem to indicate that a course laid out so that each sample-point would closely approach the mean water-content of the course would give better results than one where the percentage fluctuated widely. This is readily seen from the fact that a sample which fluctuates widely from year to year does not usually represent an average condition. Such courses as Truckee No. 2, Weber No. 1, and Granite Peak bear out this point.

From a study of the graphs obtained from our data it appears that more favorable results could be obtained by shortening the courses. The theoretically perfect course would result from omitting certain samples, but this is not practicable as it would entail much difficulty in taking the sample at the same location each year. The only method left open is to study the graphs and choose the sequence of samples that appears the most favorable.

For example, such a course as Weber No. 2 is an unwieldy course of 55 samples, which, as can be seen from the graph, could be handled much more easily, accurately, and economically by omitting all but the 17 samples from sample No. 33 to sample No. 49, inclusive. This would reduce the time and cost of the snow-surveying and by eliminating most of the poorer samples of the course would improve the reliability and value greatly.

If the first ten and the last two samples of Rubicon No. 1 were omitted, that course would also be improved as to reliability.

It would be inadvisable, naturally, to lay out a long course, take data on it for ten years or so, and then cut it down. The existing courses that are unnecessarily long might be cut down and then in the light of more experience shorter courses might be laid out that would not need as much improvement in the future.

From our study, we have come to the conclusion that most of the present courses are unnecessarily long and that with a little study they could be cut down so that better results might be obtained. Where the course is subject to drifting, it is our opinion that if the sample-points are laid out in the form of a cross, L, or T with the long side of the course parallel to the prevailing wind, errors from drifting will be minimized. Courses laid out during the summer have shown better results as obstacles on the ground that might produce misleading samples are avoided.

As to the number of samples, it will depend, of course, on the amount of snowfall and the area of the watershed to be represented by the course, but in most cases a number varying from eight to 15 should be ample if carefully selected.

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DISCUSSION

H. P. BOARDMAN (University of Nevada, Reno, Nevada)--For a number of years I have been wanting to undertake the kind of investigation covered in the paper by Messrs. Hunter and Devore. I had learned that in certain snow-courses some samples were usually higher and others lower in water-content than the average of the whole course and was anxious to see if that kind of regular irregularity was the usual condition of most snow-courses.

Last winter the two senior students of civil engineering at the University of Nevada who are the authors of this paper came to me and said they wished to work on some sort of a snow-survey project as a thesis. They readily accepted my recommendation and tackled the problem, which involved a great deal of work in tabulating data, computing percentages, and plotting graphs. I have selected five typical cases out of the 12 snow-courses they worked up and pr pared them for Figures 1 to 5.

In several cases they did not include all of the years during which the courses were surveyed but, on my suggestion, they worked from the last available survey backwards in time, since the recent years are considered better because of inspection and improvement of courses. Such inspection, starting in 1929, involved clearing of brush, etc., for ten feet or more diameter at the location of each sample, eliminating samples which were located over large rocks or logs too large to remove or which were too close to large trees. A few of the courses included were only inspected and cleared within the last two years, and several inspected five to eight years ago need it again now.

Most of my discussion will relate to the Figures 1 to 5. Figure 1 is for Granite Peak Course at an altitude of 8200 feet just over the summit on the western slope of the Carson Range

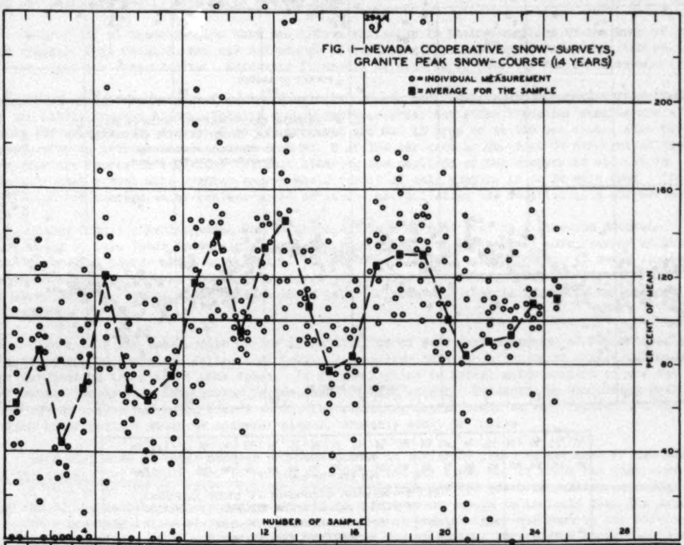
FIG. 1—NEVADA COOPERATIVE SNOW-SURVEYS, GRANITE PEAK SNOW-COURSE (14 YEARS)

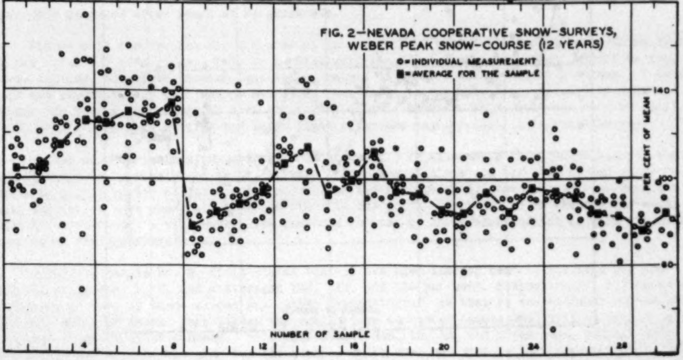
FIG. 2—NEVADA COOPERATIVE SNOW-SURVEYS, WEBER PEAK SNOW-COURSE (12 YEARS)

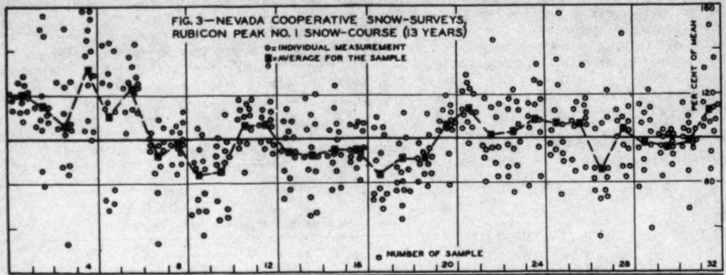

FIG. 3—NEVADA COOPERATIVE SNOW-SURVEYS, RUBICON PEAK NO. 1 SNOW-COURSE (13 YEARS)

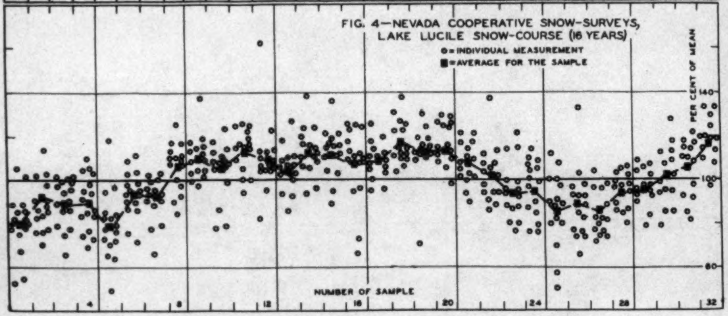

FIG. 4—NEVADA COOPERATIVE SNOW-SURVEYS, LAKE LUCILE SNOW-COURSE (16 YEARS)

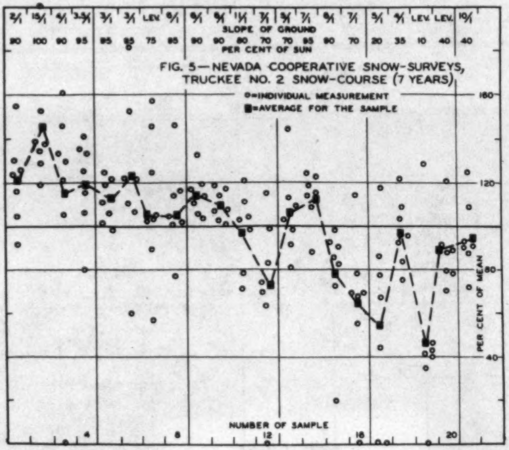

FIG. 5—NEVADA COOPERATIVE SNOW-SURVEYS, TRUCKEE NO. 2 SNOW-COURSE (7 YEARS)

about 18 miles northeasterly from Truckee, California, Tributary to the Truckee River. Each small circle represents a single measurement and, where the sample whose number is indicated at the bottom has been measured each year of the 14 years included, the space above that number should contain 14 of these small circles, each located according to its percentage of the average for the whole course for that particular survey, the percentage scale being indicated vertically at each end. On this type of graph there is no good way of indicating to which year a given measurement belongs.

This is a good illustration of a very irregular course. Adjacent sample numbers in some cases differ widely in water-content and certain numbers vary greatly in different years in relation to the mean of the course; for instance, No. 2 from 0 to 136 per cent, No. 5 from 26 to 206 per cent, and No. 17 from 68 to 284 per cent.

Nearly all of these samples show too wide a variation in their relations to the mean of the course. Phil Cowgill, who has had charge of surveying this course several times, has remarked about its irregularity. Evidently it should be altered in some way for improvement.

Figure 2 is for Weber Peak Course at an altitude of 8000 feet, near Weber Lake at the head of the Little Truckee River. This is a much better course, but a few irregular samples are evident; for example, No. 4 from 48 to 174 per cent and No. 13 from 36 to 129 per cent. Also the sudden drop in average water-content from No. 8 at 134 per cent to No. 9 at 78 per cent of the mean for the course is striking. Without altering the position of the samples at all, it is apparent that a much more regular course would result if only samples 18 to 30 were used. In that case the average water-content would be lower, necessitating the adoption of a new normal.

Figure 3 is for Rubicon Peak Course at an altitude of 8100 feet on a forested mountain slope west of Lake Tahoe and draining into the Lake. It is on the whole a more regular course than Weber Peak Course shown by Figure 2. Without shifting any sample-points, it could apparently be made more uniform by omitting the first six samples or by using either combination 7 to 19 or 20 to 32. Any one of these choices would call for some modification of the normal water-content.

Figure 4 is for Lake Lucile Course at an altitude of 8400 feet southwest of Fallen Leaf Lake and tributary to Tahoe via Fallen Leaf Lake. We consider this one of our best high-level courses for forecasting the rise of Lake Tahoe. It is the highest in normal water-content of any in our Nevada Cooperative Snow-Survey System, namely, 61.2 inches. Evidently by discarding both ends of the course and using Nos. 8 to 21, the resulting course would be very regular and the normal water-content would be somewhat higher, probably about 66 inches.

Note that some of these samples vary but little in different years in per cent of the mean of the course; for example, No. 11 ranges from 93 to 126 per cent, No. 17 about the same, and No. 20 from 99 to 129 per cent. However, these variations are too great to justify adopting any one of the samples and discarding all others. This seems enough to indicate that the average for a moderate length of snow-course with samples at regular intervals must be far more reliable than a single spot such as used by the United States Weather Bureau even though the single spot were selected after years of measurements.

Figure 5 is for Truckee No. 2 Course at an altitude of 6400 feet, two miles south of Truckee, on the north end of a ridge. This is a relatively low-level course and often subject to some early melting, sometimes showing less water-content in April 1 than in March 1 survey. I have left the discussion of this course until the last as it is the only one inspected by Messrs. Hunter and Devore in connection with their work on this thesis. This visit was made on April 13, 1937, before very much melting had taken place after the regular April 1 forecast-survey.

Rather wide variations are evident from Figure 5. In discussing this course Messrs. Hunter and Devore show by tabulation their estimate of the ground-slope and per cent of Sun exposure for each sample number of the course, as well as the average of all the per cents of mean for each sample. I have shown all of these items on the graph. This is one of the courses which I have never visited. I will make a few comments on some of the remarks of the authors resulting from their field-observations.

Regarding sample No. 2, it is stated that it averages 145 per cent of the mean for the course, while Nos. 1, 3, and 4 averaged 120, 115, and 120 per cent, respectively. I suspect the steepness of some of these slopes was rather overestimated, as that is the tendency unless one actually measures them. Very likely the small ridge mentioned causes the drifting resulting in the high relative water-content. Note that sample Nos. 15, 16, and 17 average, respectively, 78, 64, and 54 per cent of the mean for the course, which does not exactly harmonize with the idea that trees conserve the snow.

There might be some question as to the unreliableness of sample No. 18 since its average is 97 per cent of the mean of the course, though its range is fairly wide, namely, from 74 to 121 per cent of the mean of the course.

Sample No. 19 averages only 47 per cent of the mean of the course and ranges from 0 to 128 per cent. Note that this sample has only ten per cent and the next lowest sample, No. 17, only 20 per cent Sun exposure which I think would tend to decrease the losses from evaporation at all times and from winter-melting when the temperature is high enough to cause that. The inference might be drawn that the reputed protection of the trees, tending to conserve the snow, is negative. Is that inference justifiable? My field-experience in winter snow-surveying is very limited, but most of us are familiar with the fact that the snow-surface is usually depressed to a marked degree around the trunk of a large tree. This is, of course, in part due to the fact that quantities of snow are intercepted by the tree. While much of it often falls off within a few days due to wind-action or elasticity of the branches and unbalancing of the load, there is evidently a real loss from evaporation or melting or both, since the water-content of that on the ground near the tree is much less than that some distance from the tree. The authors particularly emphasize the dripping from the trees because that was in progress the day of their inspection.

I want to raise the question, which some of you may know about by experimentation, namely, does the presence of trees actually raise during winter the temperature of the air in their vicinity? My impression (on numerous occasions very vivid) is that the presence of numerous high buildings in cities does raise the temperature of the adjacent air, at least at street-level, many degrees both in summer and in winter. If the presence of trees does raise the temperature in winter, that will help account for some of the observed facts, since increases in temperature increase evaporation and melting.

This is not necessarily at variance with the probable fact that snow usually remains on the ground in forests at high altitudes for a week or two longer than out in the open mountain parks or meadows. I would explain that by saying that when in our latitude the Sun warms up enough in May and June to melt the snow rapidly in high altitudes, then the presence of the shade from the trees retards melting in the forest.

As to snow-courses, some of our inspection of snow-courses in summer or fall in recent years has resulted in eliminating samples located less than 30 or 40 feet from good-sized trees.

I am of the opinion that we will continue the type of investigation discussed in this paper, including more field-checks to try and discover the reasons for irregularities.

I believe we should show all trees near our snow-courses on the sketch-maps and also probably show topography to some extent. Profile-studies of ground- and snow-surface as cited by Dean Clyde are good and could be made to yield information similar to that contained in this paper, but would perhaps be too confusing if snow water-content profiles for 10 to 20 years of surveys were to be plotted all on the same sheet.

I am confident we can learn enough by more of these researches to be able to locate new courses of 10 or 15 samples which will give more consistent results than many of our old, longer courses. One question to be decided is what to do with our old courses. Should we locate new shorter courses in the same region entirely away from trees, or shorten old courses by eliminating parts of them, but keeping certain portions as used in the past? The latter would have the advantage of preserving the value of past records, even though new normals of water-content were necessary.

POSSIBLE RESEARCH-PROJECTS IN SNOW-SURVEYING AND STREAM-FLOW FORECASTING IN THE WESTERN STATES

Carl Elges

It is not the writer's intention in this paper to outline problems of research, give methods of attack, or to give definite locations for their research. However, problems will be advanced for the various phases of snow-surveying and forecasting for which knowledge is lacking and which should be investigated further.

In discussing these problems it is perhaps best to start with measurement of snow and follow the subject through forecasting. In the first place, it is highly desirable to have one or more mountain meteorological stations established to study the measurement of snow, evaporation from snow, temperature-effects on melting of snow and upon density of snow, and precipitation in summer. There is a decided lack of records, especially of temperature and of precipitation, in the higher reaches of the mountains where the major runoff supplying western streams originates. Take, for instance, the Humboldt Basin in Nevada which has an area of over 14,000 square miles. Less than ten per cent of this area represents the water-producing region of the Basin, yet not a single weather-station is in that portion of the watershed. Climatological records to supplement the snow-surveys would be of considerable value. This spring the snow-cover water-content in eastern Nevada on courses above 7000 feet increased ten to 20 per cent during March and at one station at 9000 feet increased 100 per cent by May 1 over the measurement received on March 1. Generally the maximum accumulation is obtained about March 1 at all but the higher stations, and the April 1 measurements show about the same amount of water or slightly less. The valley weather-stations this spring gave nearly normal temperatures during March and April, thus shedding no light upon the reason for the continued accumulation of snow and again demonstrating the necessity for high-level weather-stations.

Furthermore, the snow-cover in eastern Nevada was as low as 18 per cent density on March 1, which is considerably below that usually observed. During March and April the density increased with further accumulation of snow. A mountain weather-station could also investigate the effect of temperature on the density of snow as it is being deposited and also its effect upon the density of the accumulated snow-pack. This naturally leads to the effect of temperature on the melting of snow. Some research along this line has already been done by Church, Clyde, and others. However, there is still quite a field open for study. It is believed that the average monthly temperature is of no value as a measure of temperature because melting may be started by a short warm period that cannot be stopped again by a cold period several times as long in duration as the warm one. Therefore, it is believed that an hourly measure of temperature as advocated by Clyde must be used to obtain results. Perhaps a unit such as degree-hours above freezing might prove satisfactory. Further, there is a difference of opinion as to the result of low temperatures on total yield of a basin. Low temperatures during runoff permit deeper penetration of water and allow greater ground-water storage, some of which is returned by springs at lower elevations. Melting due to warm temperature causes a sudden saturation of the top soil and blocks deep penetration, which would require more time than is allowed by rapid melting. Low temperatures decrease the evaporation, but if little melting occurs each day the water is dispersed over a wide area a little at a time without concentrating in a channel, and this affords a greater chance for evaporation due to time and the surface exposed. The top soil has quite a range of holding capacity and will act as a sponge until the water is evaporated or taken up by plants and transpired to the air. Due to the multitude of factors which determine the yield of a basin, the writer has found no convincing evidence as to whether low temperatures decrease the yield materially. Although, it seems probable that there might be such a decrease, it is believed that its magnitude is small.

Evaporation of snow is one of the most difficult subjects to study. It is divided into evaporation without melting and that during melting. Work along this line has been carried out by Church in the Sierra Nevadas. However, no attempt has yet been made to tie evaporation in with yield from a drainage-basin by trying to determine whether excess snow evaporation due to wind-movement or other causes reduces the total obtained. Unless there is quite a wide variance from year to year, this item would bear little weight on results under the percentage method of forecasting. Chinook winds are the one serious case where evaporation is increased to an alarming rate. Very little is known regarding chinooks and these should receive attention. Since they occur more often on the east side of the Continental Divide in northern United States and in Canada, their study is necessarily limited to those regions.

The proper date for snow-surveys has been discussed before and it appears that it depends a great deal on the section of the country that is being measured. However, one group believes that the date of survey should be set and measurements obtained on that date. If a storm occurs and the survey is delayed, the data should be corrected for the increase. The other group believes that if a storm is occurring on the date of survey, the survey should be taken after the storm so that the amount of the storm will be included in the measurements because the survey should be taken at the date of maximum accumulation.

It is believed that more attention should be given to the snow-course itself. In some cases the courses are exceedingly long. By proper inspection it should be possible to lay out a short snow-course, approximately 20 measurements, which will give good results. The course should be located so as to always have a cover of snow on it for the survey so that no zero-readings will be obtained. Those courses in the open must have cross-courses to counteract the effect of wind on a single straight course. Several courses should be laid out in one region to investigate the desirability of courses in meadows or parks as against a sparse timber-covered area or aspen grove. If wind-action can be prevented on a course, there should be no difficulty in getting shorter reliable courses. Furthermore, fewer measurements will be taken by the observer with greater care, especially during adverse weather-conditions.

Nearly everyone who forecasts stream-flow from snow-surveys uses the percentage method in which the snow water-content average is computed as a percentage of normal, which normal is based upon or arrived at by comparison with the previous stream-flow from the same watershed so that the percentage of normal obtained from the snow-survey will serve as an indicator of runoff. In other words, a correlation is established between the average water-content and the stream-flow, thereby disregarding the numerous factors involved if the quantitative method were used. It is necessary, however, to study the various factors which we know affect the runoff so that the records of the past and the results of the future may be understood even though they may not be used quantitatively in forecasting.

There are several factors which directly affect the runoff. Among these is that of the soil-moisture conditions at the beginning of winter. Professor Clyde has devoted some study to this factor by taking soil-samples late in the autumn. After a record of several years is compiled, some relationship may be found that will be of use in forecasting. It is also believed that the condition of the surface of the ground, whether frozen or dry, when the first snow-storm of winter arrives, has an influence on the runoff of the next summer. If there is a frozen crust, the ground is sealed against absorbing moisture and a greater runoff is forthcoming. Data are lacking to check this and to get some idea as to the proportional effect. Furthermore, such a factor is generally lost among the many which enter in by forecast-time. Nevertheless, if possible, this item should be studied.

Where valleys are located in the drainage-basin above the gaging-point, water-table elevation studies should be carried on. This is being done in Lamoille Valley in eastern Nevada. Since no pumping is done, the water-table gives an indication of ground-water conditions in the basin and may, when a longer record is accumulated, prove of value in forecasting. It seems reasonable to believe that, for areas where underground water is pumped for irrigation, the snow-surveys may be used to forecast the water-table elevation.

One of the most important factors affecting the forecasted stream-flow is that of precipitation during the runoff-period. Unfortunately, this factor cannot be predicted and it directly affects the result obtained. The effect of this factor has been estimated to be as great as 15 per cent in the Sierra Nevadas and 35 per cent in eastern Nevada in the Humboldt Basin. Further detailed study, however, is necessary and even then it appears rather doubtful as to definite results due to the complicity of the factor itself. It has been observed that precipitation falling soon after the forecast-date has a large effect toward producing additional runoff because the precipitation falls at high elevations in the form of snow and adds to the snow-pack and at lower elevations falls on primed ground. Thus a slim year may prove to be a normal one due to normal precipitation brought on early in the runoff-period. The same amount of precipitation coming in June or July may cause only a very slight flash of the stream and add practically nothing to the runoff. Rainfall distributed in small showers during the season will also yield very little. Thus the problem becomes one of studying the distribution as to time of season and area, intensity, and amount of precipitation. So far our records of snow-surveys, stream-flow, and precipitation have repeated no season with two factors the same notwithstanding the fact that temperature, soil-moisture depletion, etc., were not being considered. It seems that the great number of factors create a different record each year.

Snow-surveys give about the best available figures as to the increase of precipitation with altitude during the winter. Studying the precipitation during the spring and summer runoff-period requires a study by a combination of snow-sampler and rain-gage since the higher elevations will accumulate snow even after May 1 and rain falls at the lower levels. A project of studying the amounts of precipitation at various elevations during the runoff-period is being started this year in Lamoille Canyon in eastern Nevada, which ranges from 6300 to 11,000 feet in elevation.

In the forecasting of lake-elevations from snow-surveys the factor of evaporation bears a direct effect on the results. First, one must know the amount of evaporation during the runoff-period in order that the rise indicated by the snow-cover can be corrected for evaporation. Secondly, if there is a variation in evaporation on a lake from year to year depending on the climatic variations, then the results obtained will be changed accordingly. It has been further suggested by Church that high winds increase evaporation far above the expected amount because of atomization due to "white caps." Experiments along this line are very difficult and are impossible by ordinary pan-observations. Perhaps a practical attack would be to use a lake whose inflow and outflow can be accurately measured and which can be equipped with recorders for elevation. Flathead Lake in Montana seems to be a possible site for such measurements.

Another field of forecasting that is now possible is that of predicting fire-hazards from snow-surveys. The Forest Service at Missoula, Montana, has found a correlation between streamflow and fire-hazard. Therefore, since the snow-survey water-content is an indication of expected stream-flow, it seems reasonable to believe that the snow-cover can be used to forecast fire-hazards. The snow-surveys have been started only the past two years in the area mentioned and, therefore, the record is of insufficient length to give results at present. It is possible that other areas where snow-surveying has been practiced for a longer time may speed this study.

Further study is being given the subject of normal at the Nevada Agricultural Experiment Station. At present the various agencies are comparing stream-flow to average water-content of snow-courses by graph or percentages of normal with or without corrections for such factors as precipitation during runoff, temperature, and absorption. With further study it is hoped that the actual runoff can be corrected for these factors to that which would occur under normal conditions. However, it appears that the percentage of normal of snow should be given a little thought in these comparisons.

The writer has been reducing both the normal of snow-cover and the average water-content each year in Lamoille Basin by a constant amount assuming that the snow-cover present minus a constant for retention would be a better indicator than the total water-content. Of course, the retention is not truly a constant but nevertheless it stands to reason that that portion which is most effective on runoff would be a better indicator than the same portion plus a constant or variable quantity which is acting in the opposite direction or reducing the flow. The record for Lamoille Canyon is very short as to runoff but, for the few years that are available, the results have been very encouraging. Under this system 100 per cent water-content still gives 100 per cent runoff. Generally speaking, when the whole water-content was used, a snow-cover of 50 per cent would not mean a 50 per cent runoff but perhaps only 30 per cent. Similarly a snow-cover of 150 per cent would produce a runoff greater than that figure. By reducing the survey average water-content and the normal by a constant amount, the 50 per cent water-content should produce a 50 per cent runoff and the 150 per cent snow-cover a similar percentage of flow. When time permits, the writer plans to extend this study of normals.

Many of the above-mentioned problems have been given thought and study and some have been partially solved. Any knowledge gained is of course of value. However, each stream or basin is a case in itself with some yielding more readily to analysis than others.

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WEIGHT VERSUS MELTING METHOD FOR DETERMINING DENSITY OF SNOW

J. J. McNutt and W. B. Alcorn

Snow-surveys and Weather Bureau precipitation-station measurements have been made simultaneously at Bechler Ranger Station, Yellowstone National Park, during the winters of 1935-36 and 1936-37. This circumstance has afforded an opportunity to compare density-measurements of snow by the two methods, that is, by weight through use of Mt. Rose snow-sampler, and by the Weather Bureau "melting" method. Furthermore, the results are of particular value because the observers in this case are especially qualified to do careful work of this kind, having had considerable laboratory-experience.

The findings show, with one exception, the density of snow as determined by the "weight" method to be higher than that procured by the "melting" method. The discrepancy amounts to nearly three per cent in some cases, which is serious in view of the use to be made of the data. The question is raised as to whether the error is owing to faulty design of the Mt. Rose snow-sampler, or an environmental defect in the "melting"-method procedure.

Table 1 sets forth the measurements and calculated density of the snow as determined by the "melting" method at a single location for the Weather Bureau. and the average measurements and density along the snow-course.

Table 1--Water-equivalent of snow by weight and melting methods

Date	Melting method			Weight method		
	Snow-depth	Water-content	Density	Snow-depth	Water-content	Density
	inches	inches	per cent	inches	inches	per cent
			Measurements by Mr. Rhodes			
Dec. 31, 1935	41.0	8.47	20.65	39.9	9.6	24.06
Jan. 31, 1936	70.25	18.25	25.97	70.7	20.6	29.13
Feb. 29, 1936	81.70	26.45	32.13	87.5	29.1	33.25
Mar. 31, 1936	84.10	31.48	37.43	86.7	31.0	35.71
Apr. 30, 1936	22.0	10.20	46.30	33.6	15.9	47.32
			Measurements by Messrs. McNutt and Alcorn			
Dec. 31, 1936	26.0	4.38	16.84	26.4	4.46	16.89
Jan. 31, 1937	58.0	11.05	19.05	59.5	13.10	22.01
Feb. 28, 1937	71.5	20.69	28.93	71.4	22.20	31.09
Mar. 31, 1937	68.0	24.00	35.30	68.0	24.80	36.50

It will be noted that the same observers are not responsible for both years' records. It was during the second year that they became especially inquisitive about the quite consistent discrepancy in results of their work.

They called for a more sensitive weighing-scale for their Mt. Rose snow-sampler and, upon being supplied with it, checked results to within one per cent by using both scales.

It was thought that different packing of the snow at points along the snow-course and at the point where the sample for melting is procured might account for the disagreement. Thus, on February 28, 1937, snow-cores for density-determination by both methods were very carefully drawn within one foot of each other. The snow-depth was 71.4 inches. By the "melting" method it was found to be equivalent to 20.42 inches of depth of water by Mr. McNutt and 20.96 inches by Mr. Alcorn. According to the "weight" method the equivalent water-depth was found to be 22.1 inches. Thus, the two methods gave an average difference of 1.4 inches of depth of water.

The exact procedure followed by these men in applying the "melting" method is reported by Mr. McNutt as follows:

(1) The 8-inch diameter United States Weather Bureau rain-gage overflow-attachment was placed mouth downward and pressed vertically downward until filled with snow.
(2) The snow was worked away in a vertical section with a shovel to the depth the attachment was pushed down.
(3) A flat-surfaced shovel was inserted across the mouth of the attachment.
(4) The attachment with its snow-contents was carefully removed from the snow-section and inverted.
(5) The attachment filled with snow was taken into the house. A measured amount of warm water was poured over the snow until it was all melted. The same amount was then taken out of the total and thrown away. The remainder was carefully measured in the measuring tube by means of a standard United States Weather Bureau measuring stick. The above procedure was repeated until a complete core was obtained.

In discussion of these results with H. G. Carter, Meteorologist in charge of the Weather Bureau Station at Boise, Idaho, it developed that the trouble might lie with the "melting" method for the following reasons:

(1) It is very difficult to procure an accurate sample of snow-cover for the "melting" method where the depth requires the taking of several samples.
(2) The upper edge of the rain-gage overflow-attachment is rather blunt and, therefore, it may require that considerable pressure be exerted in pressing this receptacle into the snow. The combination of forces thus exerted on a snow-crust are such that the pressure within the sample area is double that outside. It, therefore, appears likely that a crust may break immediately under the sampling receptacle and be pushed outward rather than into the sampler.
(3) There is no provision for releasing air from the top of the sampling can while it is being pushed downward into the snow, which undoubtedly may cause some of the snow to blow out at the bottom of the sample.

(4) Some water may be wasted in the several operations required in melting and measuring a snow-sample.

The authors suggest that the fault may lie in the design of the Mt. Rose snow-sampler. Also, Dean G. D. Clyde of Utah State Agricultural College thinks likewise. Their explanation is that the slots in the particular snow-tube used are too wide. When the snow is more than three feet deep and consists of loose granular particles, it is thought that the snow-tube coupling breaks loose snow-particles and they fall alongside of the tube and enter the slots. Mr. McNutt states that his records show that this does not occur materially when the snow is less than three feet deep nor after the snow-cover becomes solidified late in the season.

Yellowstone National Park,
Wyoming

APPLICATION OF SNOW-SURVEY DATA BY THE BUREAU OF RECLAMATION

O. C. Reedy

(Published with the approval of the Commissioner, U. S. Bureau of Reclamation)

The United States Bureau of Reclamation is essentially a construction and operation rather than a research organization. This distinction holds in the snow-survey work as well as in other phases of the Bureau's activities. While in snow-surveying, as in other fields, original contributions may from time to time be made by the Bureau, its primary interest in the work is in obtaining and applying the data.

The Bureau has used or expects in the immediate future to use snow-survey data for forecasting runoff on several watersheds, among which are the Okanogan in Washington, the Malheur in Oregon, the Boise in Idaho, Jackson Lake in Wyoming, and the Colorado River Basin in connection with the operation of Boulder Dam. The last two of these are of the most importance and general interest.

Snow-surveys have been made and used in forecasting runoff of the Jackson Lake watershed since 1919. Observations are made at nine stations which were selected as the most strategically located of about 20 points observed the first two years. The course-method was not used until the spring of 1937, but at each station a number of measurements are made to find the average depth and water-content. The circuit for the surveys is made each month during the spring, usually between the fourteenth and twenty-first. The average water-content for the nine stations is expressed as a percentage of the mean of the readings during previous years. The data as actually used in the past have been general rather than exact, and usually have been interpreted in terms of the extent to which Jackson Lake Reservoir would fill. This information is particularly important because of the joint ownership of both the bottom and top storage in Jackson Lake, and the attendant difficulties of administration of the water. An accurate knowledge beforehand of the available supply simplifies the handling of this storage.

In studying the general problem of snow-surveying the accuracy of both the March and April surveys on this area has been determined. Graphs were developed showing the relation between water-content of the snow-cover in percentage of normal and runoff from the date of the survey to July 31, for the years of record. Entering the graph with the percentage of normal of snow-cover for any year permits prediction of the runoff. The estimates have been compared with the actual runoff and the difference expressed as a percentage of the estimate. Judged by this method, the March surveys show a mean error of ten per cent and the April surveys a mean error of 12 per cent. No attempt was made in this study to allow for varying ground-saturation conditions or other factors influencing the percentage of runoff from the snow, although these factors are introduced in a general way into the forecasts made in the project-office after each survey.

Eventually the most extensive use of snow-survey data by the Bureau of Reclamation will no doubt be in connection with the operation of Boulder Dam recently completed on the Colorado River. The coordination of the uses of Lake Mead for river-regulation and flood-control, irrigation water-supply, and power-production will be difficult, especially since operation for flood-control and irrigation uses must be given first consideration, and yet power-sales must furnish the revenue from which the costs of construction and operation will be paid. Snow-survey data have not as yet been very extensively used, first, because the need of forecasts is not yet as great as it will become upon more complete development of power-possibilities or under circumstances when water must be wasted to secure flood-control storage-capacity, and, second, because the snow-course data have not been available for a long enough period to establish reliable normals.

It is probable that the data will eventually be used to forecast runoff from the time of the survey to July 31 from each of the component parts of the Colorado River Basin, and the total inflow to Lake Mead determined therefrom. Two-thirds of the water entering the Lake each year comes during the spring flood-period and is derived from melting snow. Of this amount the main Colorado River in Colorado contributes 28 per cent and the Gunnison River 14 per cent. The Bureau is at present concentrating its activities on these two watersheds as being the most important and also the most accessible on which to make forecasting studies. Data are, however, being secured on other watersheds through the cooperation of other agencies.

The forecasts will probably be made by relating the percentage of normal of water-content of the snow-cover in a given watershed to the runoff from that watershed, by the use of charts showing these relationships for the years of record. It is not improbable that the data from courses in any one watershed will have to be weighted to compensate for the unequal relative distribution of snow and snow-courses over the area. This is a refinement that must be based on several years of experience in the operation of the courses and in forecasting, and may be eliminated by judicious location of the courses. A similar refinement may have to be introduced to account for the year-to-year change in the condition of the ground and other variables, but because of the large area of the basin under consideration these factors may average out except in the most extreme years.

A much more important source of difficulty is the complete change that may occur in the snow-cover over the basin during the month of April due to late snows. This change has been sufficient in past years to have required a revision of the plan of operation of the reservoir during the month. An organization geared to make snow-course readings only once a month cannot be expected to secure data in the middle of the month, but it is not at all difficult to secure a mid-month record from a precipitation-station, by telegraph if necessary, and for this reason precipitation-records will be used in connection with the snow-course data. The Bureau is now operating 26 stations, strategically located to supplement the net of Weather Bureau stations.

Snow-course data were used indirectly this year in the forecast of Lake Mead water-surface elevations. The forecast was necessary to determine the time at which the Secretary of the Interior could announce that firm power was available for sale, as required in the power-contracts. In 1935 and 1936 forecasts had been made, based on precipitation-records from selected stations throughout the basin. A similar forecast was not made this year, but, instead, a comparison was made of snow-conditions as they existed in 1936 and 1937, based on the March first snow-surveys of these years. This comparison was related to the forecast of 1936 and an estimate of the inflow for 1937 obtained, from which reservoir-levels were computed. Anticipated releases must necessarily be used in such a forecast of reservoir-levels, further complicating the problem. The way in which the actual levels have followed the estimates has been very gratifying, even to the extent that there has not yet been any need to apologize for the roundabout method of the forecast.

It is anticipated that the form for setting up forecasts for the entire basin, using both snow-surveys and precipitation data, will be developed this summer and fall, and that forecasting of Colorado River runoff will be put on a permanent basis next season.

U. S. Bureau of Reclamation,
Denver, Colorado

SNOW-SURVEYS AND RUNOFF-FORECASTING FROM PHOTOGRAPHS

H. L. Potts

From times of earliest antiquity man has attempted with more or less success to forecast or predict coming events. Various methods and devices have been used in attempting to attain this end. We have passed from the oracles of Ancient Greece, through various forms of witchcraft and oriental mysticism, to the more modern methods of collecting and analyzing scientific facts and data. It is true that, while progress has been made, the goal has by no means been reached. We are still hampered by many obsolete methods and superstitions. This field of research is by no means crowded and many opportunities for study and investigation still exist.

We of the semiarid states are particularly interested in any and all problems pertaining to water and water-supply, fully realizing that not only our prosperity but our very existence is dependent upon this vital element. During the last few years many beneficial contributions for the betterment of mankind have been made by various eminent students in this field, and many new phases of the problem are, we have every reason to believe, in the process of solution.

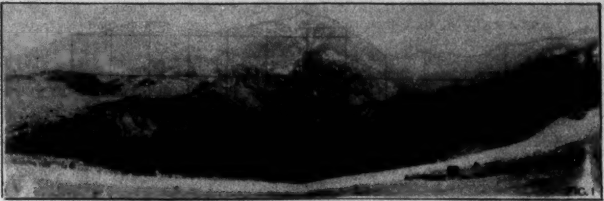

FIG. 1

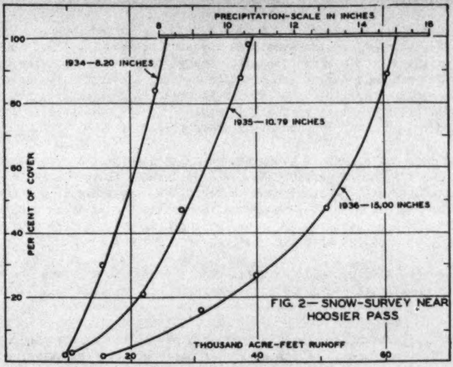

FIG. 2— SNOW-SURVEY NEAR HOOSIER PASS

The forecasting of runoff and water-supply has long been a problem of general interest and has intermittently engaged the efforts of the writer for a number of years. It is on the possibilities of forecasting stream-runoff by means of photographs which will be submitted in this paper.

Being directly interested in the domestic water-problems of the City of Denver, the studies were confined to the headwaters of the South Platte River, from which we derive our principal supply.

The amount of water flowing in our streams comes from two sources: (1) The melting snow which has accumulated on the high mountain ranges during the winter, and (2) the rains of summer falling on the watershed. It is, therefore, necessary to consider both of these factors in forecasting the runoff of a stream.

The collection of the basic data for this study was begun in the spring of 1934 by photographing a section of the Continental Divide near Hoosier Pass, at the headwaters of the Middle Fork of the South Platte River. This section of the range is high and rugged, and contains many small canons and gulches which drift full of snow during the winter. These immense drifts seldom completely disappear during the summer, and it was for this reason that this particular spot was selected. An automatic recording-station was installed a few miles downstream to measure the runoff from the area and a precipitation-gage was established nearby.

A series of photographs was taken of this section of the range at intervals throughout the year, and the percentage of the area covered by snow in each photograph was calculated and recorded, each photograph being taken from the same point on the hillside.

In determining the percentage of cover a transparent template was superimposed on the photograph, as indicated in Figure 1, the template, however, having each square indicated in the Figure divided into 100 smaller squares. Each small square was counted in which snow appeared and the total number of small squares counted divided by the total number of small squares in the template indicated the percentage of the observed area covered by snow. Each photograph taken was thus measured, the same identical area being observed in each case.

At the end of the season, or on November 1, when the streams at this altitude usually freeze up and make further measurement impractical, the total runoff was calculated from the date on which each photograph was taken to the end of the season on November 1.

A chart, shown in Figure 2, was prepared on which these data were plotted showing the percentage of cover and the measured runoff for each photograph. A runoff-curve was drawn in for the year on which was noted the recorded rainfall during the period of observation. The records for the years of 1935 and 1936 were likewise plotted on the same chart with the result that three separate curves were obtained for the three individual years, each year showing considerable variation in precipitation.

If the theory is correct that runoff from snowfall may be accurately determined by means of the area-method as shown by photographs, the distance between the three individual curves should be approximately directly proportional to the differences in the recorded precipitation. A precipitation-scale was laid out on the chart connecting the curves representing the extreme years. This scale was intersected by the middle year at almost exactly the point representing the recorded precipitation for that year. This would seem to prove the correctness of the theory and that the method is worthy of further study and consideration.

In making the forecast of runoff it is necessary to determine the normal amount of precipitation falling during the runoff-period. An additional curve is then drawn on the chart to represent a normal or average year. A photograph is taken, say about May 1, and the percentage of cover measured. Then from the point of intersection on the "normal-year curve" shown on the chart, and the percentage of cover shown by the photograph, we read directly the amount of water which can reasonably be expected from the observed area for the season.

By calculating the ratio between the total runoff from this area and the total diversion at the City Intake for an average year, the total amount of water which will be available for use is determined.

The method is apparently very flexible in that other ratios may be used as required, or, in the event that indications seem to denote a year of deficient precipitation, a curve may be sketched in for any amount of rainfall which, in the opinion of the forecaster, may be expected.

Additional years of record will undoubtedly add to the accuracy and value of this study. Certain minor changes in methods may be made from time to time as appear necessary, but it is our opinion that runoff from accumulated snows in certain areas may be forecast from photographs with more accuracy than we have been able to attain in the past. The advantages of observing a relatively large area will, we believe, more than compensate for the various minor errors which are known to exist in this method.

Denver Water-Board,
Denver, Colorado

LUNCHEON CONFERENCE AND ROUND-TABLE PRESENTATION OF EXPERIENCES AND PROBLEMS IN SNOW-SURVEYING

R. L. Parshall, presiding

Appreciation and resolutions--After the luncheon, June 26, 1937, L. K. Sherman expressed the thanks and appreciation of all members present for the very splendid programs which had been arranged by the Committee. Appreciation was also expressed to the Young Women's Christian Association for the comfortable room which was furnished for the use of the meetings, as well as the splendid food which was served in the dining room. Appreciation was also expressed to the City of Denver for the ease with which the whole conference of the American Association for the Advancement of Science had been arranged and managed. A resolution of thanks was taken.

Mr. Tipton, as Chairman, replied expressing his appreciation to the members of his Committee for their very fine assistance and cooperation. Dr. Church spoke of the intelligent way in which the Committee had worked. Information concerning the program was obtained from headquarters and the Committee carried on the program without any muddling.

Mr. Tipton expressed the thanks of all to Mr. Mitchell for operating the lantern throughout the week and to Mrs. Harriet T. Whitehouse for recording the Luncheon Conference.

Papers and discussion--The first paper of the afternoon was "Snow-surveys and runoff-forecasting from photographs" by H. L. Potts, Water Rights Engineer, Denver Water Board. This paper is printed above in these *Transactions*. In discussing Mr. Potts' paper, Dr. Church asked if Mr. Potts were judging by areas of white and said he had found it impossible to use feather-edge snow, but estimates must be made from large snow-banks. Mr. Potts said the gulches where these studies were made were deep and the snow-drifts were solid. The pictures were taken as the snow began to melt and as the season progresses the large areas shrink. The pictures taken year after year look very much the same, but to get the best results it is necessary to have what might be called ideal conditions.

Mr. Farrow asked when the speaker began to take the first pictures each year and Mr. Potts replied any time after April 15. Melting begins soon after that. Mr. Houk asked if forecasts were made at any time during the year and the reply was "Anytime up to November 1." Eighty per cent of runoff comes during the months of July and August. Mr. Parshall made the observation that precipitation in the South Platte Area during the summer was not great. Mr. Farrow asked if the zero-point in the observations would not depend upon the date observations were started. However, it was brought out that the first pictures were made each year at approximately the same time--April 15--and that runoff did not start until some time after that.

A movie film of snow-surveying in the High Sierra by George A. Lewis of the Los Angeles Department of Water and Power was presented. There was some discussion of the best things to carry in the way of food--chocolate bars, raisins, tomato juice, etc. It was especially stressed that a snow-surveyor must never eat snow or drink snow-water (without boiling), as the former dries the mouth and the latter puts the stomach in disorder. After the film Mr. Parshall expressed the thanks of everyone to the Los Angeles Department of Water and Power for the use of the film. Mr. McLaughlin said that north of where these pictures were taken the Power Company agreed to send men for survey if the Government would pay their compensation. However, there were no Government funds available but private funds made the survey possible. Mr. Horton remarked that in 1902, 1903, and 1904 both State and Federal funds were used for surveys and the same thing was necessary today. Dr. Church spoke of a film of the Wasatch Range by Dean George D. Clyde which was well worth seeing.

Round-table presentation of experiences and problems in snow-surveying

Following a discussion on snow-courses by Ralph L. Parshall of the United States Bureau of Agricultural Engineering, O. C. Reedy and Mr. Parshall spoke of the difficulty in ascertaining a good snow-course, and it was brought out that to get a true idea of the possibilities of a snow-course the location should be examined in the winter. The selection of locations for snow-courses in summer is difficult.

Merrill Bernard, in charge of the River and Flood Division of the United States Weather Bureau, introduced the subject "Deficiencies in hydrologic research." He spoke of a report on problems of hydrologic research being prepared by the Water Resources Committee of the National Research Council. He spoke of the work of this Committee and read a tentative list of snow-survey research-projects proposed by a Subcommittee. He suggested that comments from those present would be valuable to the Subcommittee and Committee in preparing the final report. It was decided that Mr. Tipton would see that each man received a copy of the proposed questions and the replies and comments made would be returned to Mr. Tipton, who, in turn, would see that they reached the Committee in Washington. It was suggested that the Committee would welcome comments on research-projects for any branch of hydrology, in addition to snow-surveying. Mr. Bernard brought out that the Committee has the services of a qualified man to put material into proper form. Fundamental research in connection with extending flood-surveys may be included.

Mr. Boardman asked, if these suggestions are carried out, what organization will do it. Mr. Bernard pointed out the report will merely show the deficiencies in the hydrologic research. The purpose is to encourage every agency to undertake this research. It is hoped to stimulate research in many localities and get away from the idea that research should be done only by the Government. Much can be done by students, or other research-agencies, when they feel they are not duplicating research undertaken by the Government.

In the last few years the interest in hydrologic study and research, and use of hydrologic data, have multiplied many fold. Mr. Bernard spoke of the change in attitude toward the Weather Bureau and its ideas for expansion.

Mr. Parshall spoke of the chance of duplication of ideas unless each bureau had some means of notifying the others of its activities. Mr. Shulits spoke of a report gotten out every six months by the National Bureau of Standards so that all governmental agencies may know what the others are doing in the matter of research. It is known there is much overlapping of activities on the part of the various governmental agencies, and it was felt something should be done to prevent this as much as possible.

H. O. Caperton asked if there is some way to supplement the high snow-course data by low-course data on the route to the higher elevation. He spoke of the course at Loveland Pass as being 11,000 feet, and that he felt that supplemental data at 9000 to 10,000 feet would be beneficial. Mr. McLaughlin agreed that it was very helpful in predicting runoff when lower-course data are available. Mr. Marr spoke of a United States Geological survey of stream-channels where the survey was made from the bed up to the top at 1000-foot intervals and it was felt this will prove of great value in flood-predictions.

Messrs. Church and Parshall offered a resolution that the attention of the United States Geological Survey be called to the importance of topographic maps which will permit the determination of zones of various elevations in drainage-areas at 1000-foot intervals where runoff is a particular problem. It was felt that if this service was to be offered it should be more or less complete and not sketchy in nature. Dr. Church said that the Sierras are practically completely covered by topographic information, and Mr. Parshall said Colorado was only about 25 per cent covered. It was stated further that, while the State Engineer has been cooperating with the United States Geological Survey in extending this service in Colorado, there is still a great deal to be done.

Discussing "Problems in measuring precipitation in connection with watershed and hydrologic studies," R. S. Goodridge of the United States Soil Conservation Service talked of the problem of measuring snowfall and runoff in the Ohio Valley over broken topography, with limestone base. He made the following remarks:

"The members of the South Continental Divide Snow-Survey Conference may be interested in the problem of snow-surveys on the experimental watershed of approximately 4600 acres located in east-central Ohio in the North Appalachian Region.

"This project, established November 1935, is being conducted by the Soil Conservation Service, United States Department of Agriculture, under the general direction of Dr. W. C. Lowdermilk, Associate Chief and Head of the Division of Research, and the immediate direction of C. E. Ramser, in charge of the Section of Watershed and Hydrologic Studies. This Section of the Research Division is engaged in the study of hydrologic phenomena of watersheds ranging in size from a few acres up to about 5000 acres.

"The objectives of these studies of the experimental watershed are, briefly, to determine quantitatively the effect of improved land-use and erosion-control practices on soil- and water-conservation; to determine the extent to which land-use and erosion-control practices are effective in the control of floods; and to collect and interpret data on rates and amounts of runoff resulting from precipitation of various amounts and intensities on agricultural areas ranging in size from small watersheds of a few acres to those of 5000 acres for the economic design of erosion-control and flood-control structures. Further, the experimental watershed must develop an adequate technique for the assembly and routing of surface-flows and the procedure of extrapolating to larger stream-systems.

"It is seen from these objectives that the hydrology of runoff and floods forms the dominant function. In this, snow plays an important part, and quantitative measurements are essential. The problem of snow-measurement differs here from that of the usual snow-courses established and operated for the prediction of spring and seasonal runoff. On the experimental watershed, the snowfall-depth and water-equivalent will be measured at sufficiently frequent intervals to aid in the effort to account for all meteoric waters and their distribution. It is apparent that the snow-surveys must be as complete as possible.

"A brief description of the physical characteristics of the watershed and something of the instrumentation may serve to give a background to the problem of snow-surveying on the area. The North Appalachian watershed is drained in a southwesterly direction by Little Mill Creek, one of the headwaters of the Muskingum River and a part of the Muskingum Conservancy District. The area lies just south of glaciated terrain and the soils are of the Muskingum series, loam and silt-loam in texture. The land-use is divided roughly as woodlot 20 per cent, and pasture and cultivated, each at 40 per cent, with general farming predominating in the region. Approximately 60 sub-watersheds will be studied with the aid of artificial stream-gaging controls and stage-recorders, over 100 rain-gages and a central meteorological station, 40 or more ground-water observation-wells for special studies, soil-thermographs, and other special instruments. Electrical circuits will be used for synchronizing the time-charts of many of the stage, rainfall, and other recorders. Elevations range from 800 feet to approximately 1300 feet above sea-level. For this watershed, 29, 8, and 63 per cent of the total area, the ranges of slope in per cent are approximately 0 to 12, 12 to 20, and 20 upward, respectively. Similarly the aspects of this watershed are divided in terms of per cent of area as follows: North, 10; south, 10; east, 5; west, 10; northwest, 10; southwest, 25; northeast, 20; and southeast, 10. These physical characteristics, particularly slope and aspect, are significant in the measurement of rain, hail, and snow.

"The watershed is crossed by latitude 40° 21' north and falls in a climatic region unfavorable to continuous snow-cover throughout the winter; nevertheless, preparations for measuring depths of three to ten feet or more must be provided. Wide variations in depth, together with discontinuous snow-blanket,tends to make the problem of snow-measurement for our purposes more complex than in the usual case of following a snow-course once or twice a season.

"Definite procedures have not been worked out yet, though it is probable that the commendable work in the Adirondack Area of New York State will serve as a guide in the formulation of a procedure. The spring-scales and cutting and weighing tubes developed by the Bureau of Agricultural Engineering have been provided for present use. It is felt, however, that snow-courses alone will not be sufficient for the purposes of these studies involving so many small watersheds, under diversified land-use, slopes, and aspects. Early plans include supplemental use of snow-boards.

"Initial installations and procedures will be made as flexible as possible to provide for the adoption of improved methods as they develop from your Committee and from the work of other agencies interested in snow-measurement.

"The Section of Watershed and Hydrologic Studies sincerely appreciates this opportunity of participating in this Conference and, although we have little to contribute from our own experience, we hope we may benefit from the knowledge, judgment, and advice of this group and that we may be enabled thereby to contribute to the art of snow-surveying."

It was pointed out by Dr. Church that the ground itself is a good base for cutting snow-samples providing the entire snow-cover is being measured. In the case of new snow fallen upon an earlier snow-cover, snow-boards insulated by muslin or pieces of canvas could be used as a base, provided the snow is not so greatly drifted at the boards as to give erroneous results. If the old snow is crusted, it will be easy to separate the new snow from the old, and obtain an accurate weight. An average of many measurements will greatly increase accuracy particularly where quantitative measurements are desired. The effectiveness of snow over usual rains in increasing and controlling runoff was stressed.

Hail must naturally be measured in terms of water to determine its water-content rather than its momentum efficiency. Because of the relatively large interstices between the hailstones, measurement by depth only cannot be employed.

Experiments insampling tapioca snow and hail might well be made to determine the best diameter of snow-sampler for such purposes. Possibly the Kadel type of sampler would satisfy. The relative diameter might well conform to the usual size of hailstones. Only the outer case of a rain-gage would suffice to catch hail and this case should be sufficiently deep to prevent escape by rebound. A 15-inch can of considerable depth, such as is used for weighing the heavier mountain snows, might be most satisfactory.

It was felt by everyone that snow should form the central feature of all precipitation-measurements. Mr. Bernard felt that the present method of using snow-gages for measurement of snowfall was subject to high error and should be supplanted by some method of snow-surveying to determine the precipitation storm by storm.

Acknowledgments

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